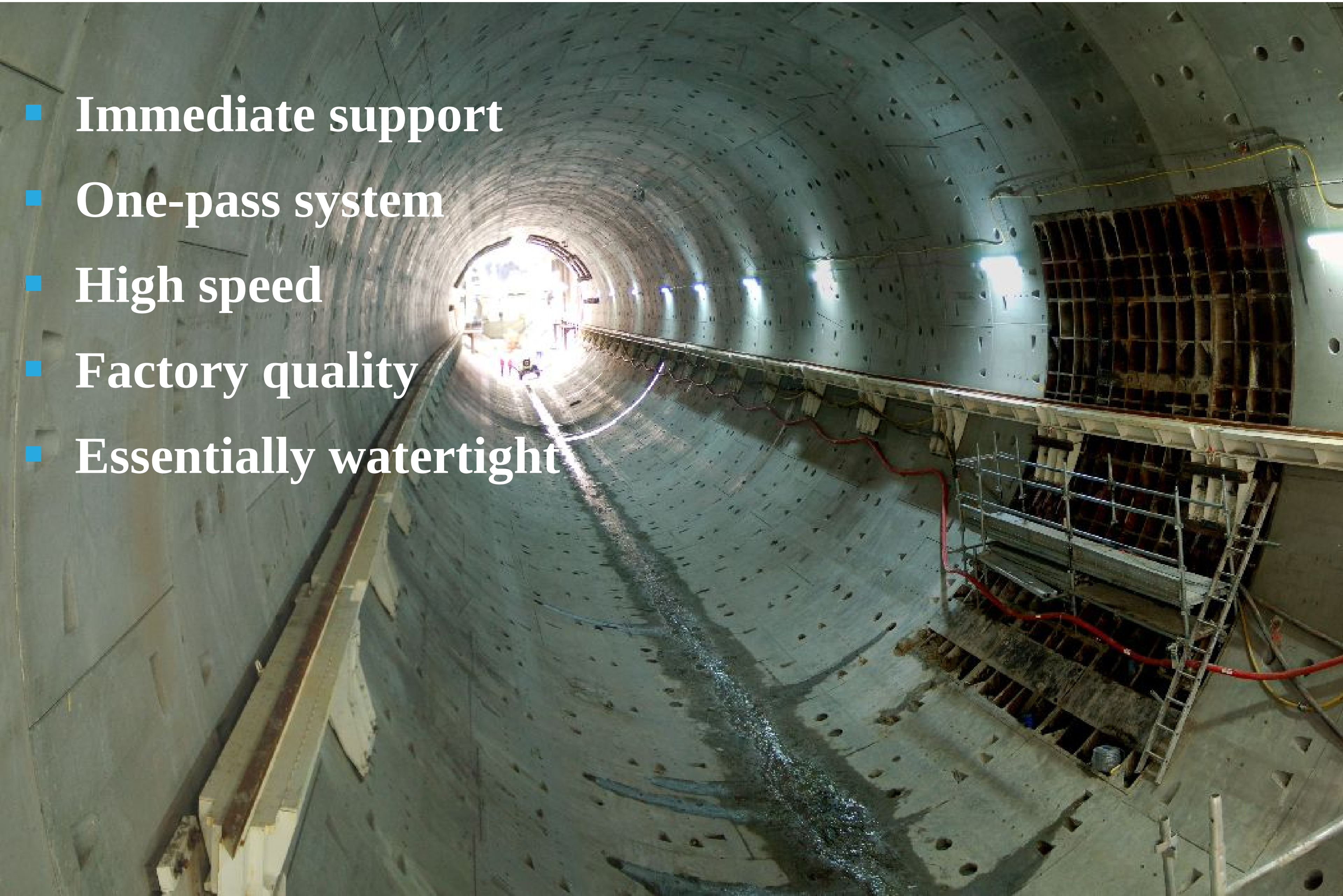
Precast concrete segmental liners

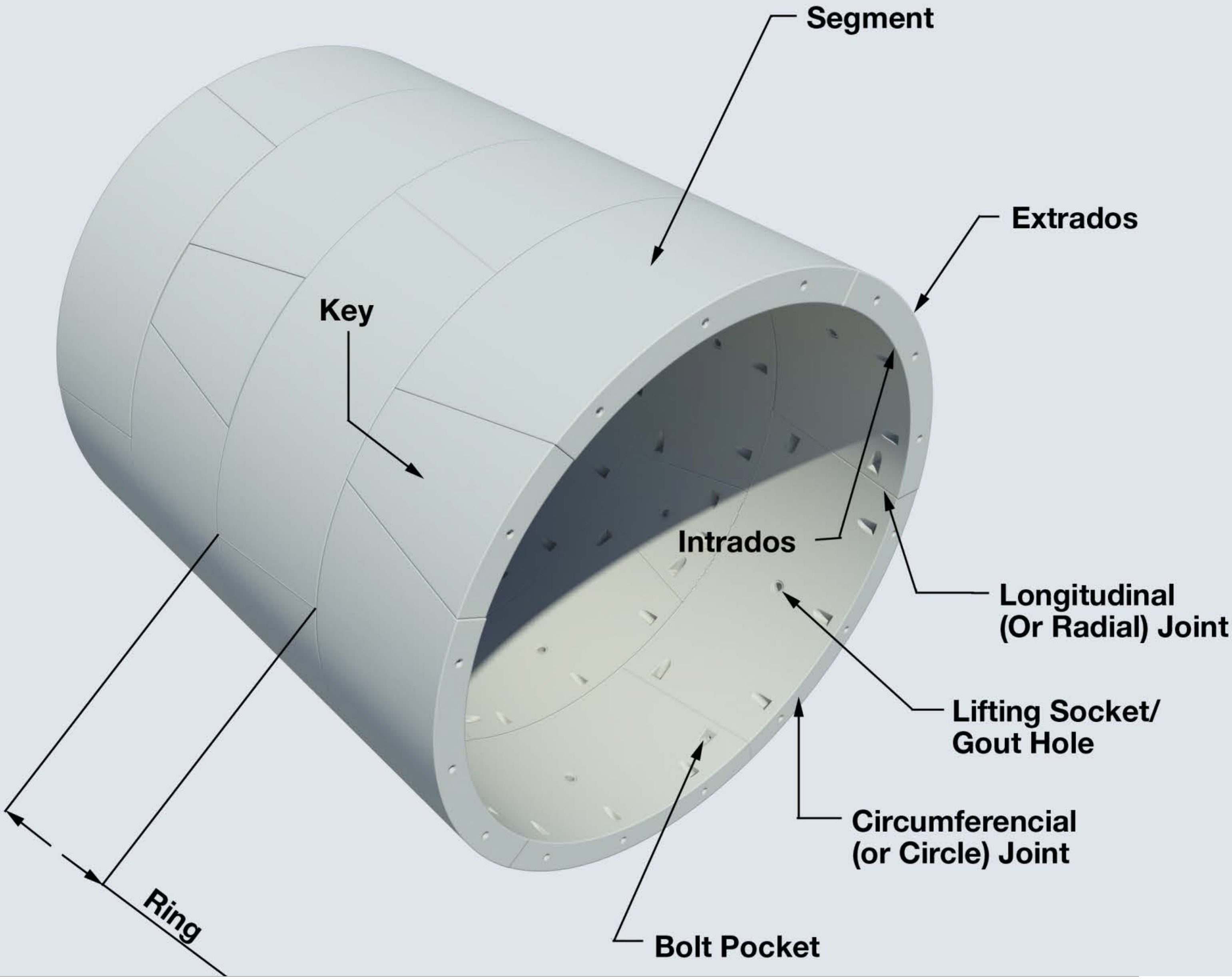
Jon Hurt

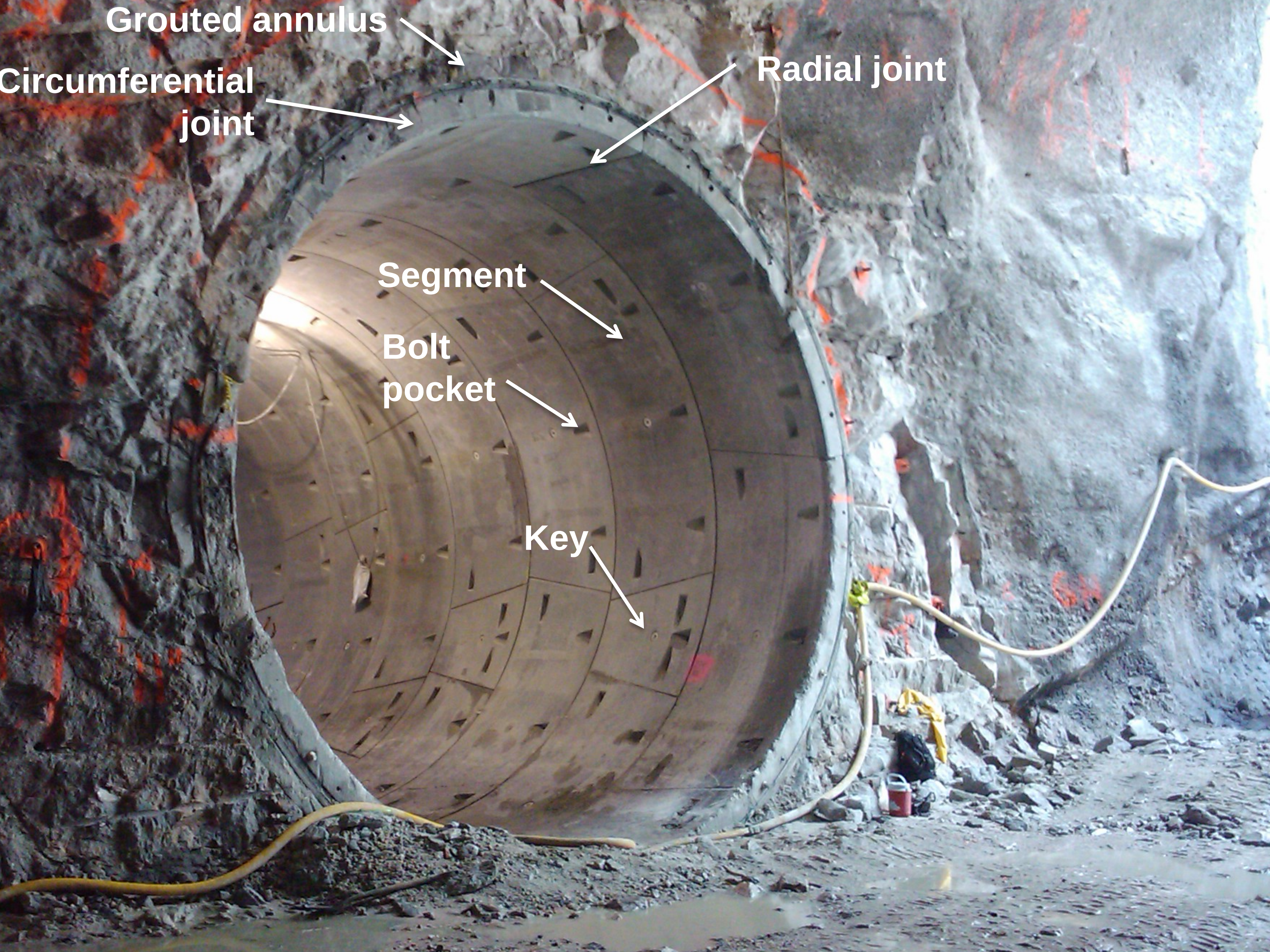
ARUP

Introduction to Segmental Linings

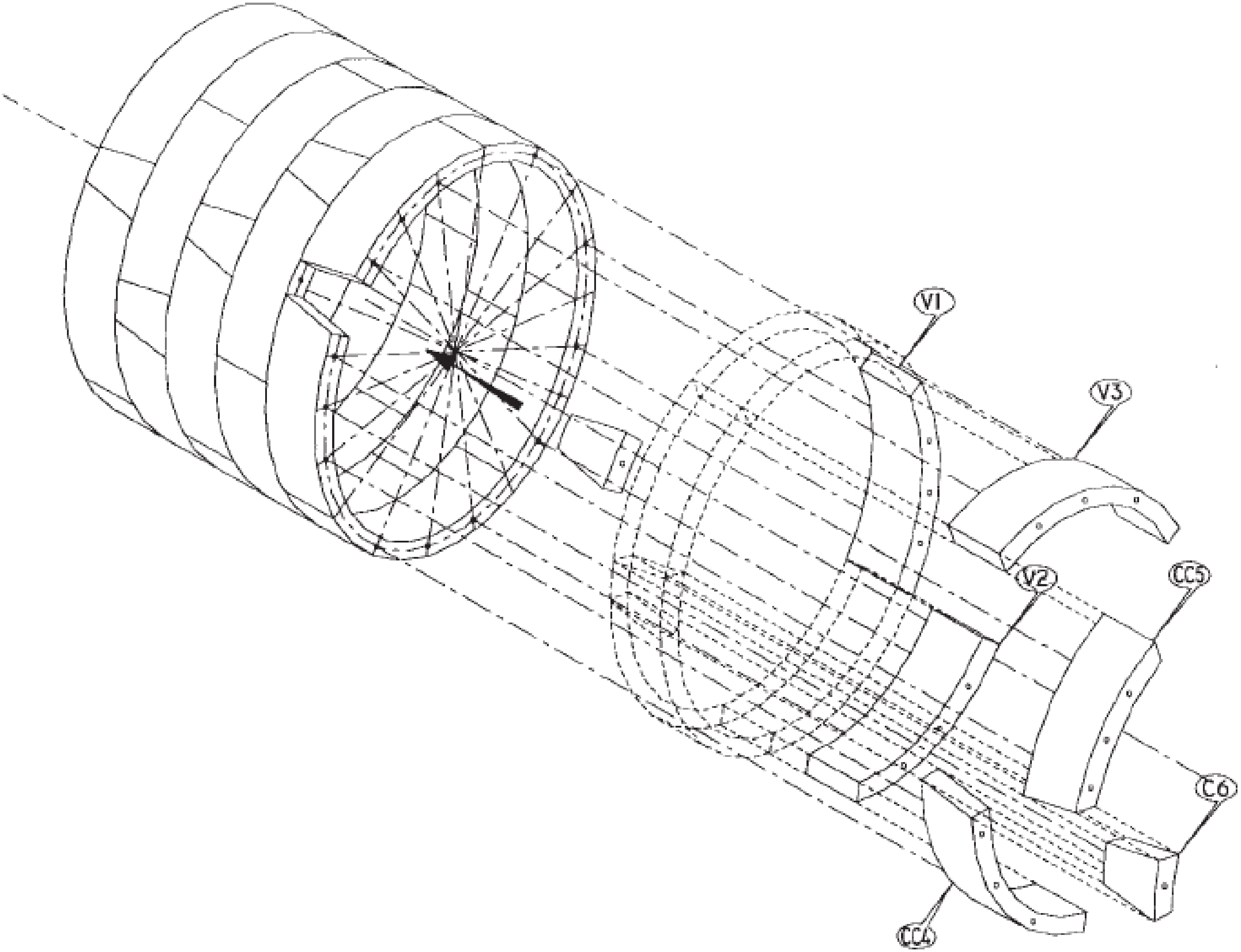


- Immediate support
- One-pass system
- High speed
- Factory quality
- Essentially watertight

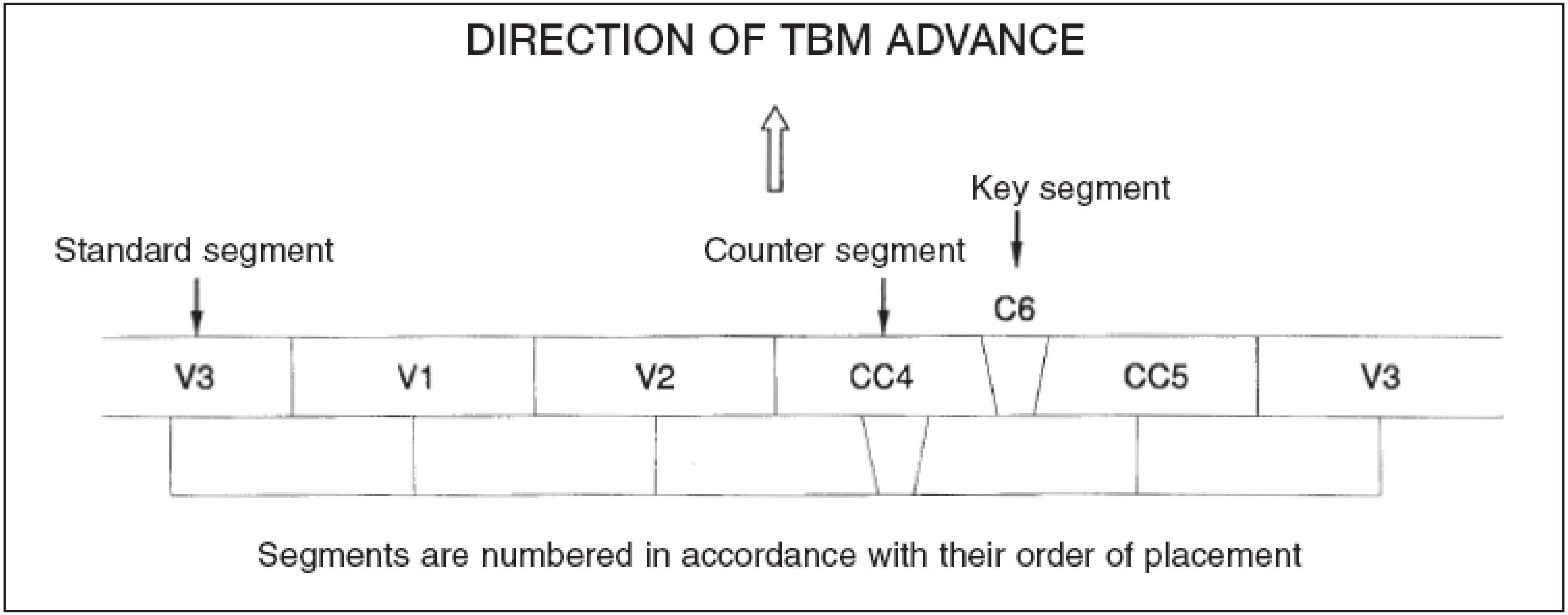

Segment
Extrados
Key
Intrados
Longitudinal
(Or Radial) Joint
Lifting Socket/
Gout Hole
Circumferencial
(or Circle) Joint
Ring
Bolt Pocket


Grouted annulus
Circumferential joint
Radial joint
Segment
Bolt pocket
Key

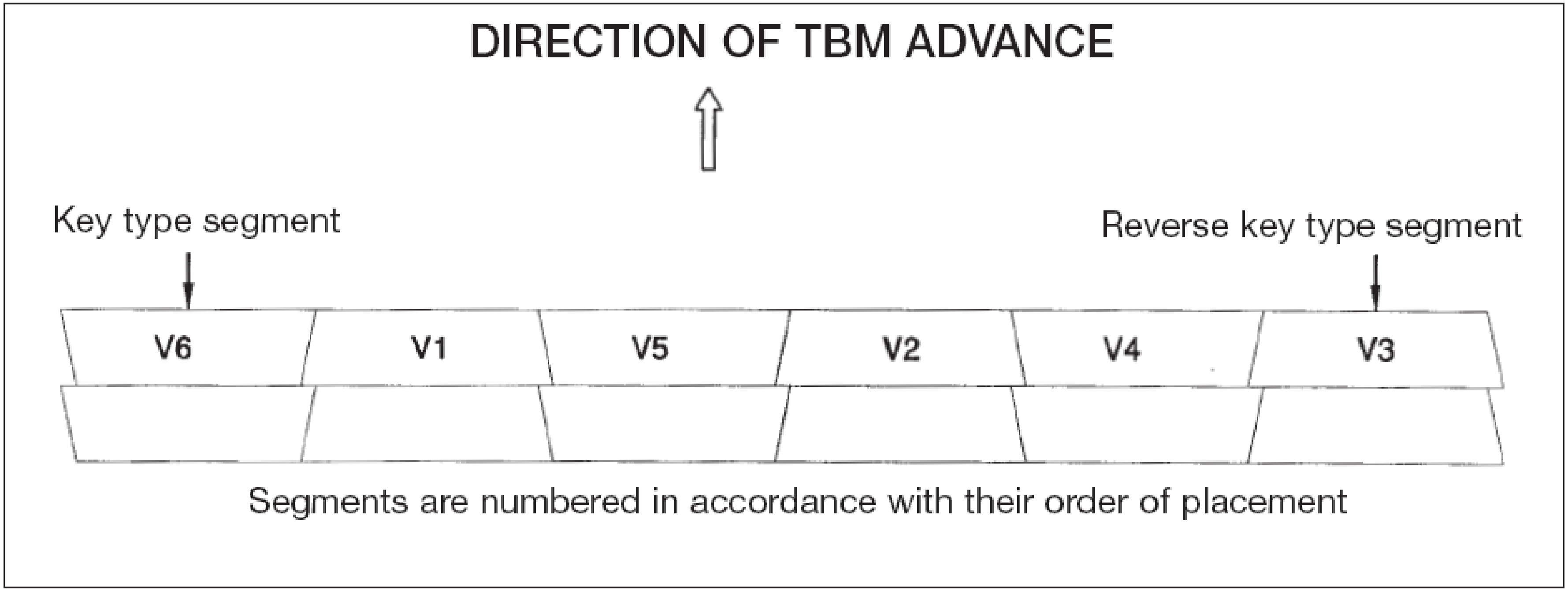
Rectangular Lining



Rectangular Lining

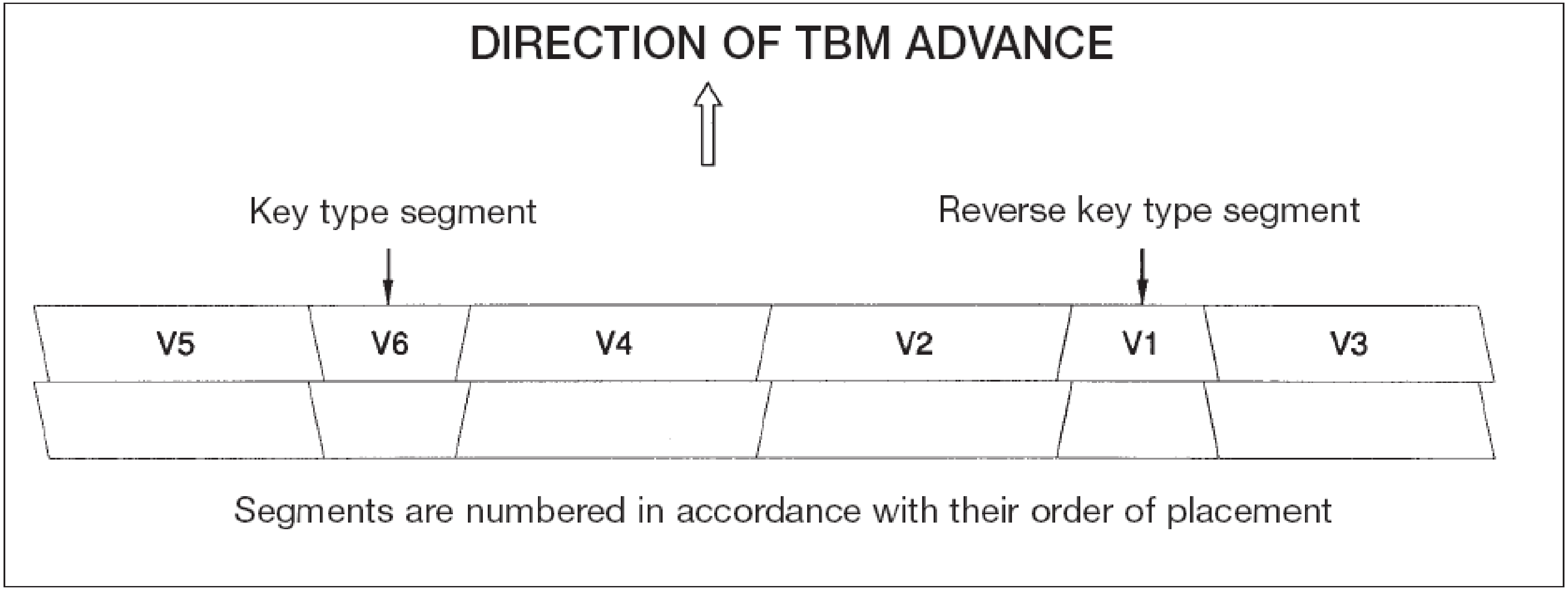


Trapezoidal Lining

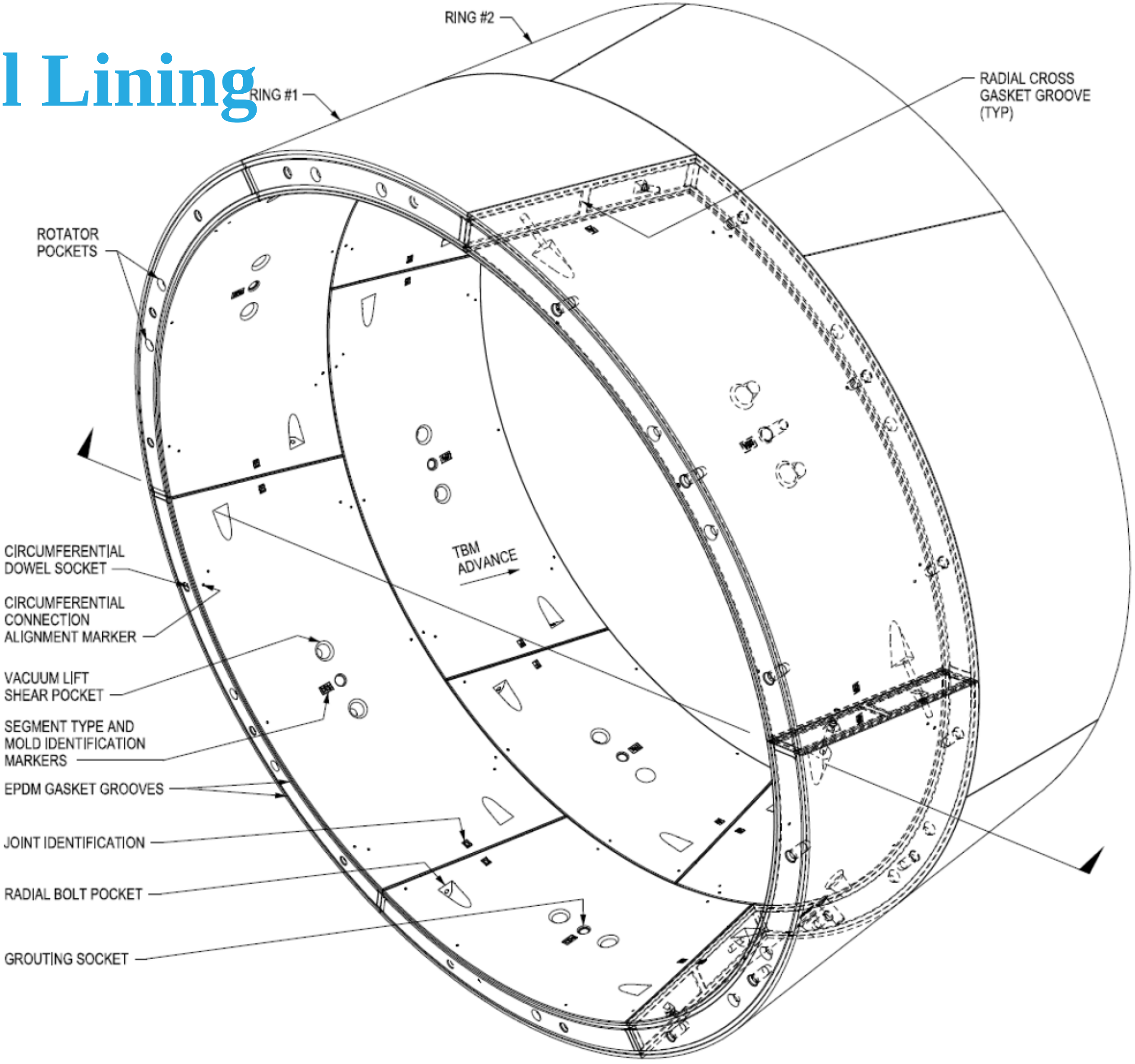


Segments are numbered in accordance with their order of placement

Rhomboidal Lining



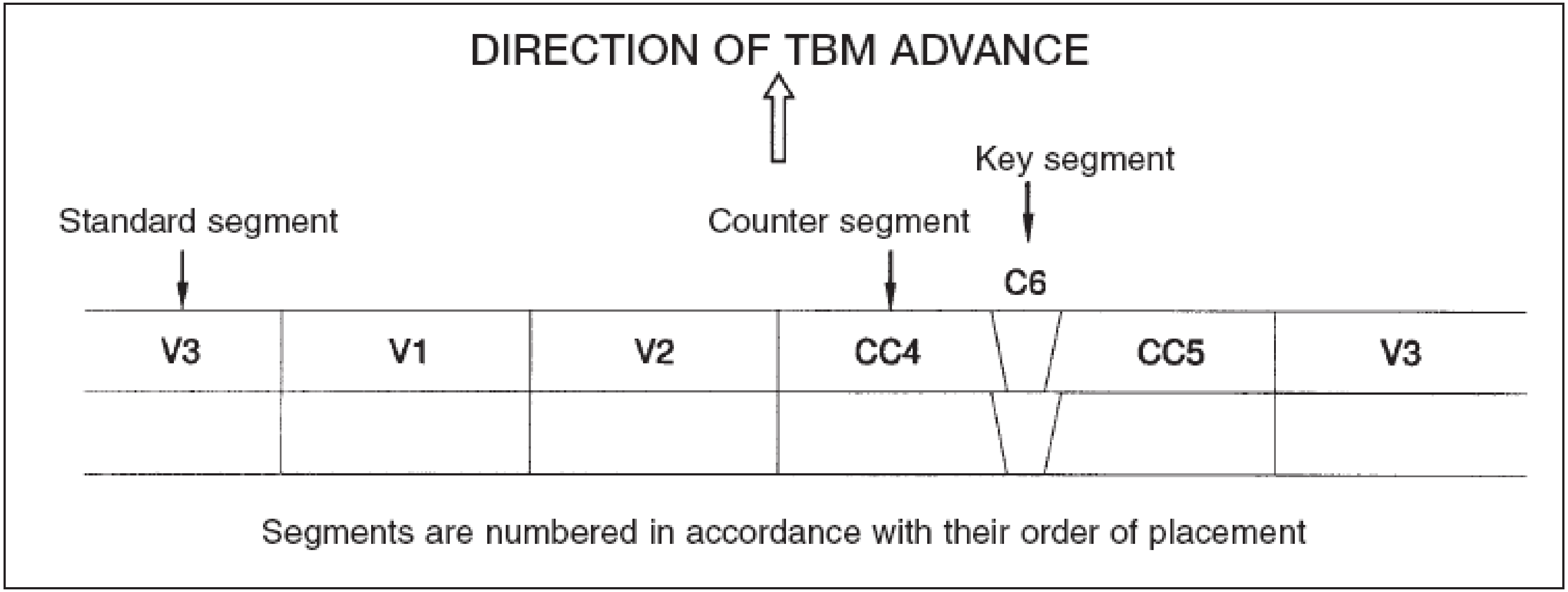
Rhomboidal Lining


RING #2
RING #1
RADIAL CROSS GASKET GROOVE (TYP)
ROTATOR POCKETS
CIRCUMFERENTIAL DOWEL SOCKET
CIRCUMFERENTIAL CONNECTION ALIGNMENT MARKER
VACUUM LIFT SHEAR POCKET
SEGMENT TYPE AND MOLD IDENTIFICATION MARKERS
EPDM GASKET GROOVES
JOINT IDENTIFICATION
RADIAL BOLT POCKET
GROUTING SOCKET
TBM ADVANCE

TUNNEL RING ASSEMBLY - ISO. VIEW

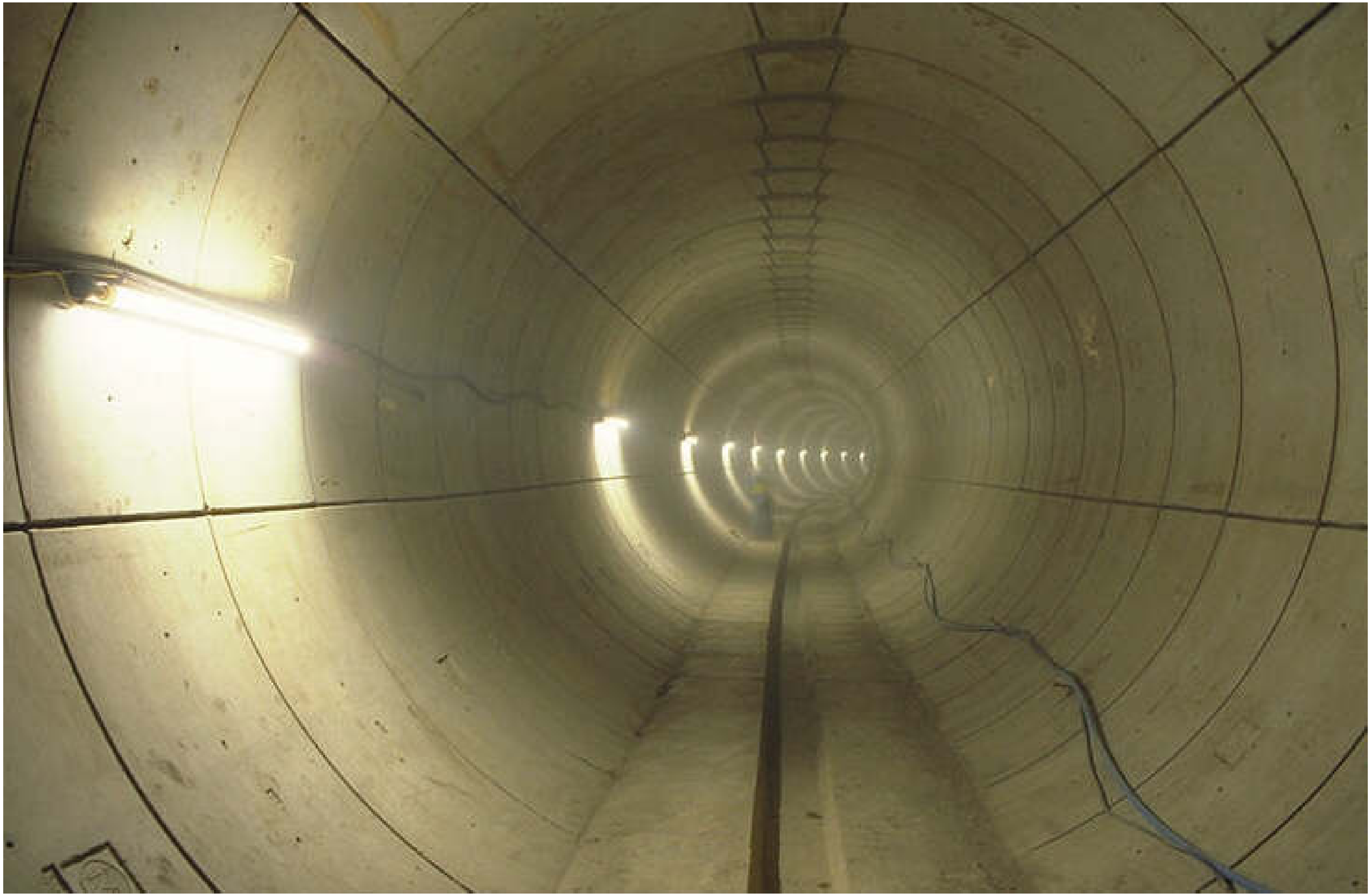
NO SCALE

Expanded Lining

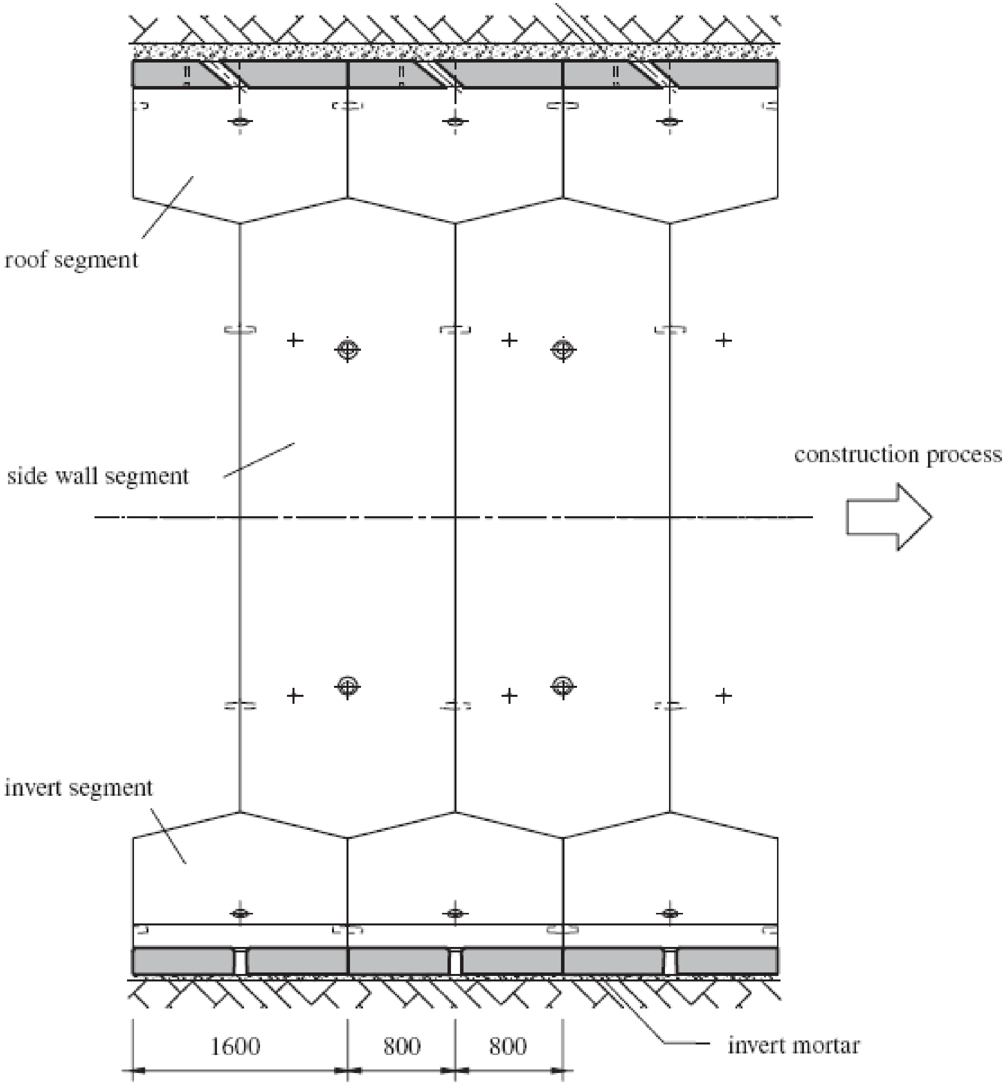


Segments are numbered in accordance with their order of placement

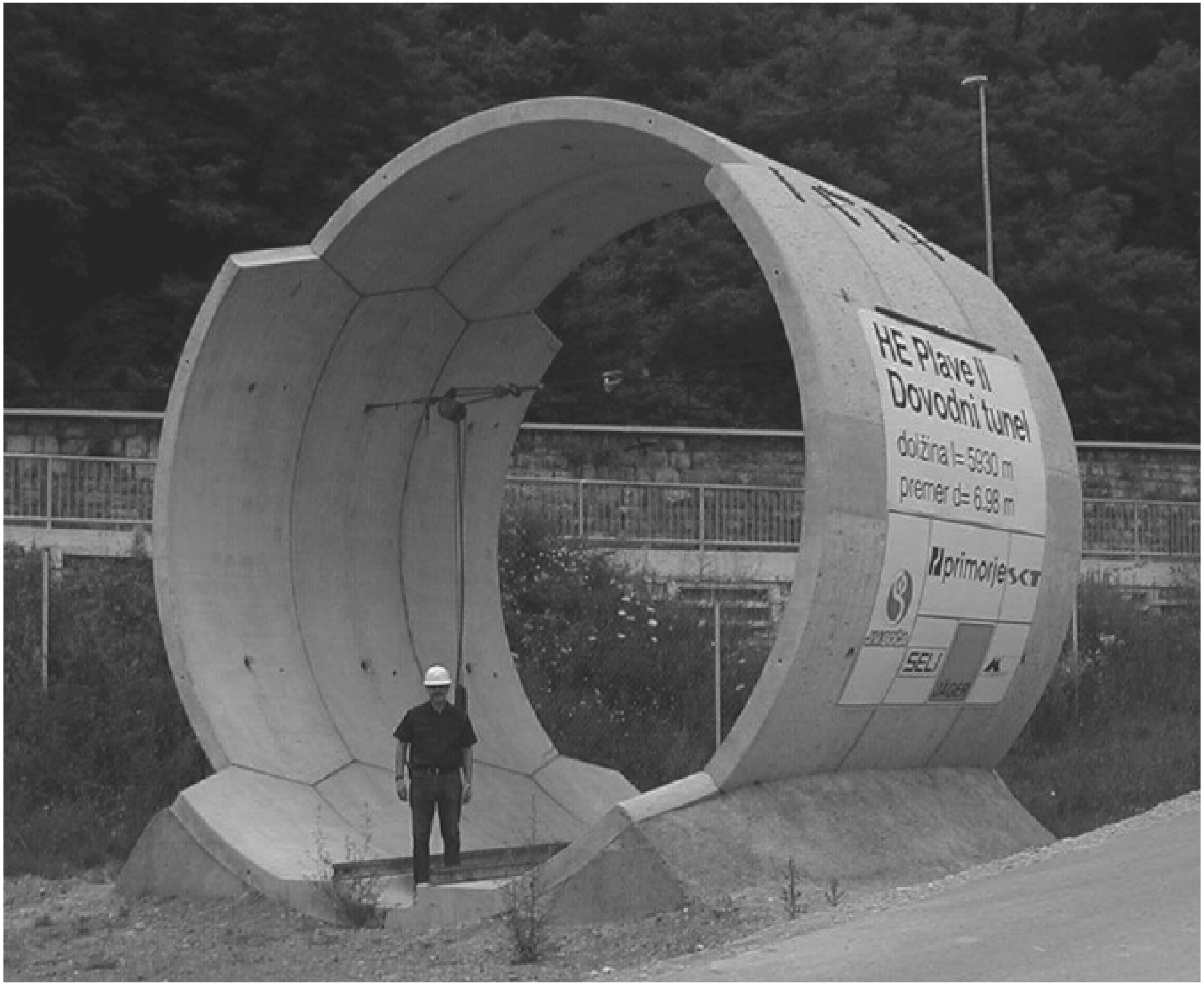
Expanded (Wedgeblock) Lining



Hexagonal (Honeycomb) Lining

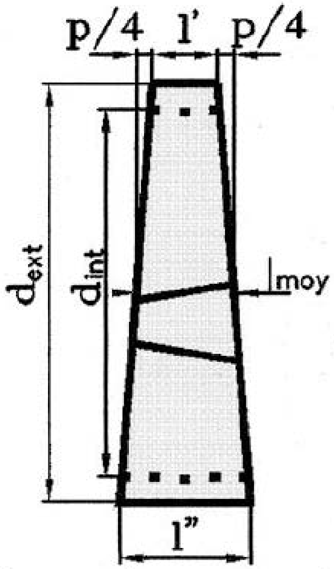


Hexagonal (Honeycomb) Lining

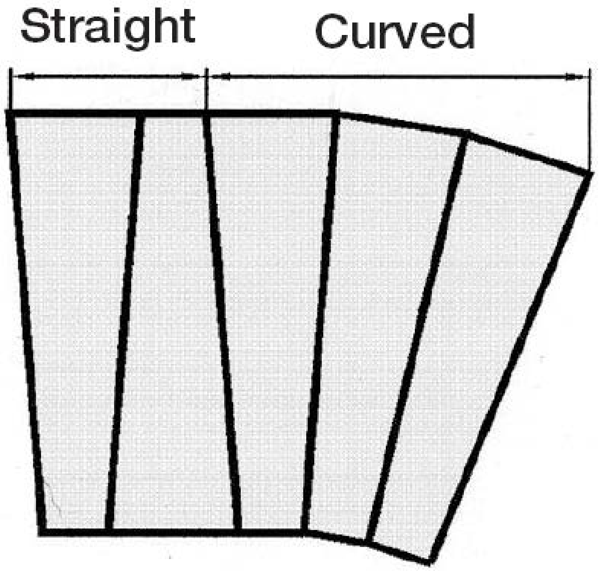


Tapered Linings

- **Taper can be applied to any lining geometry that allows rotation of rings**
- **Limits need for packing between segments on curves**

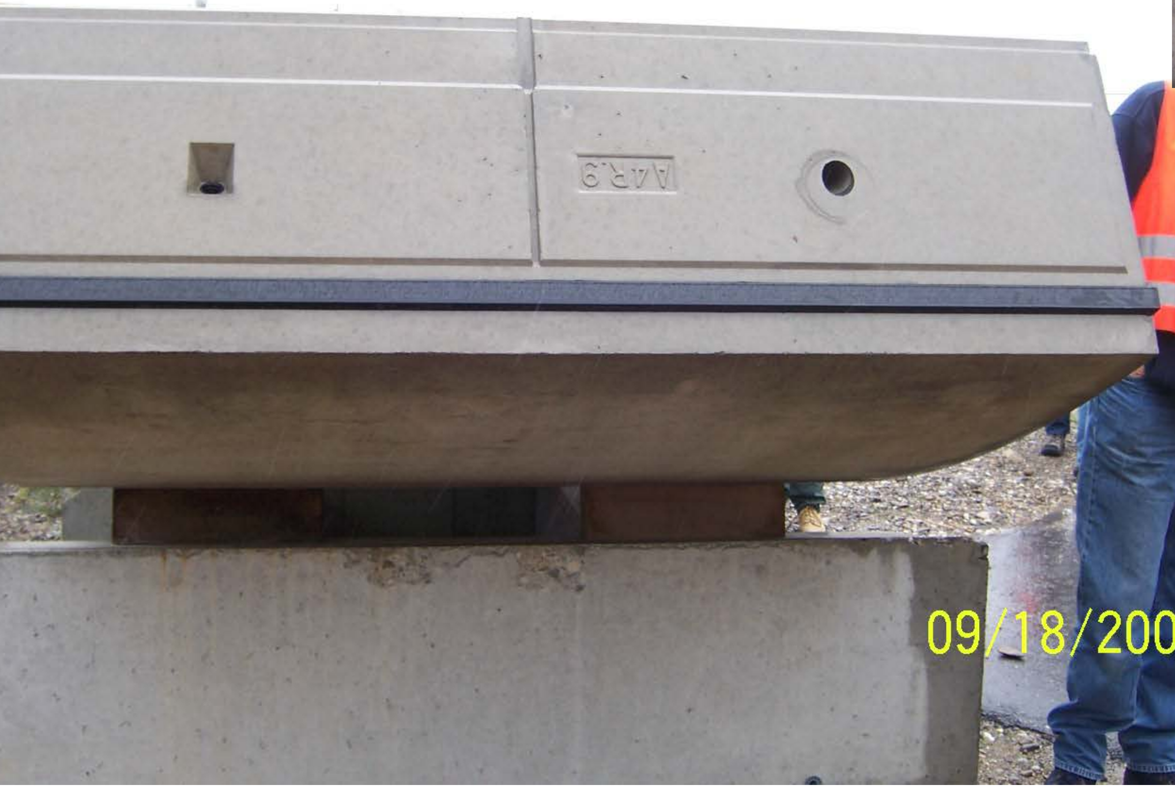


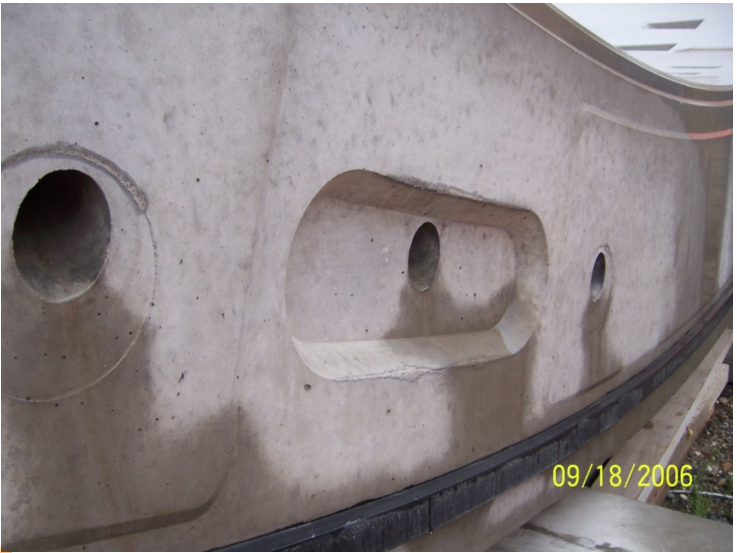
Universal tapered ring

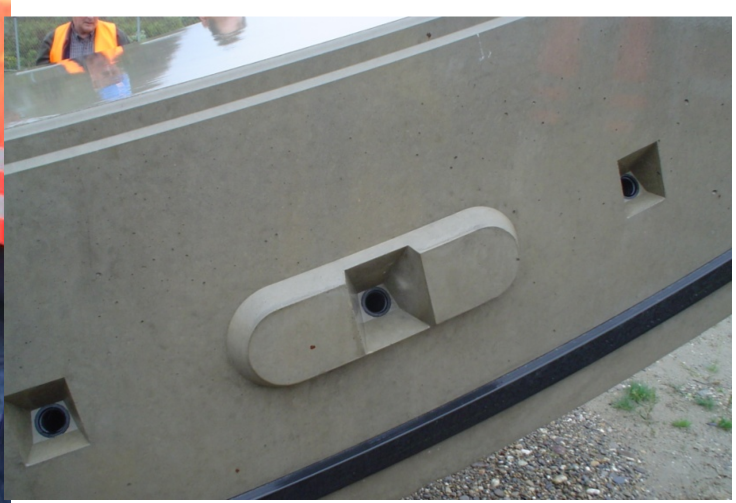


Plan view

Joint Geometries







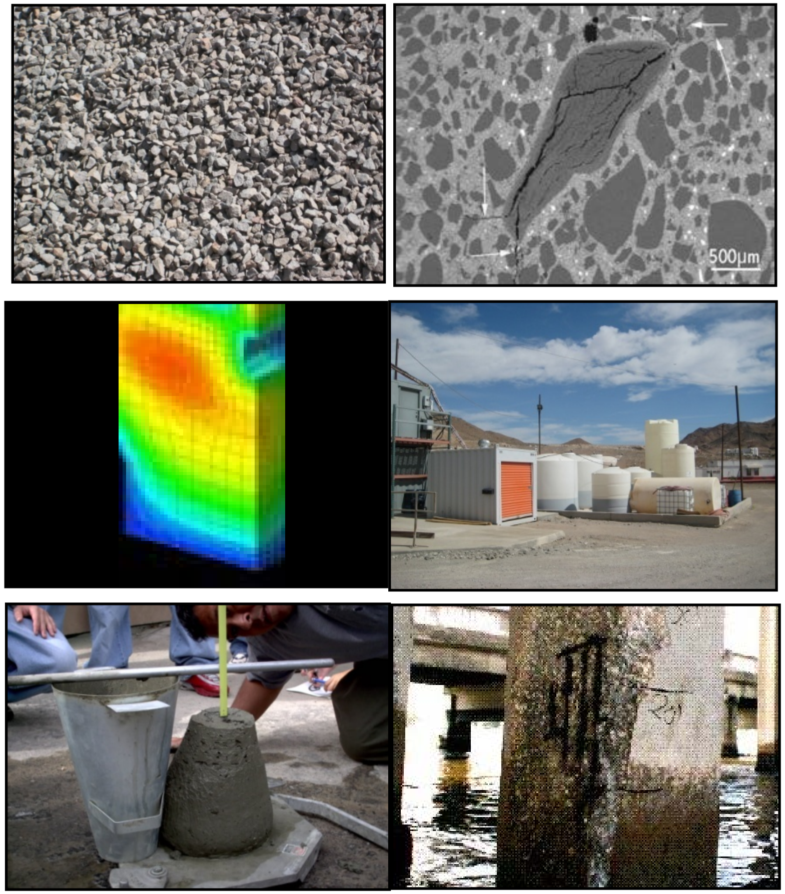
Materials

- **Reinforced Concrete**
- **SFRC**
- **Polypropylene Fibers (Fire resistance)**
- **Resistance to Hydrogen Sulphide attack**
- **Steel/SGI**

Concrete

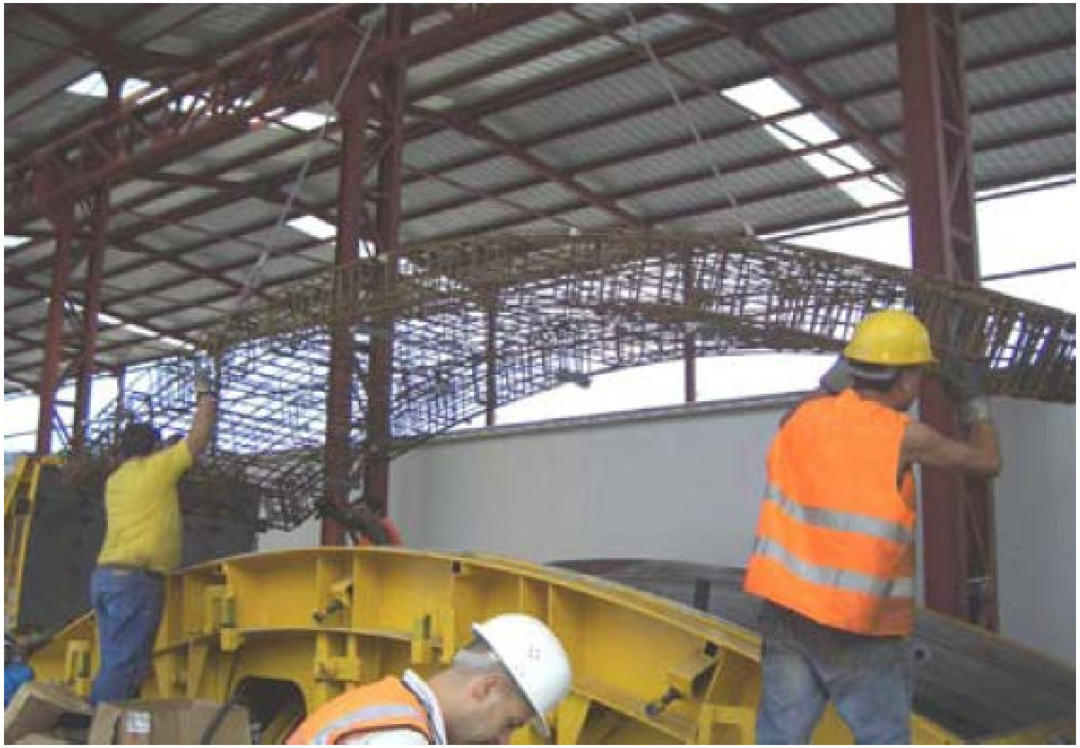
Typically require:

- **dense, impermeable, durable mix**
- **high early strength**



Reinforced Concrete

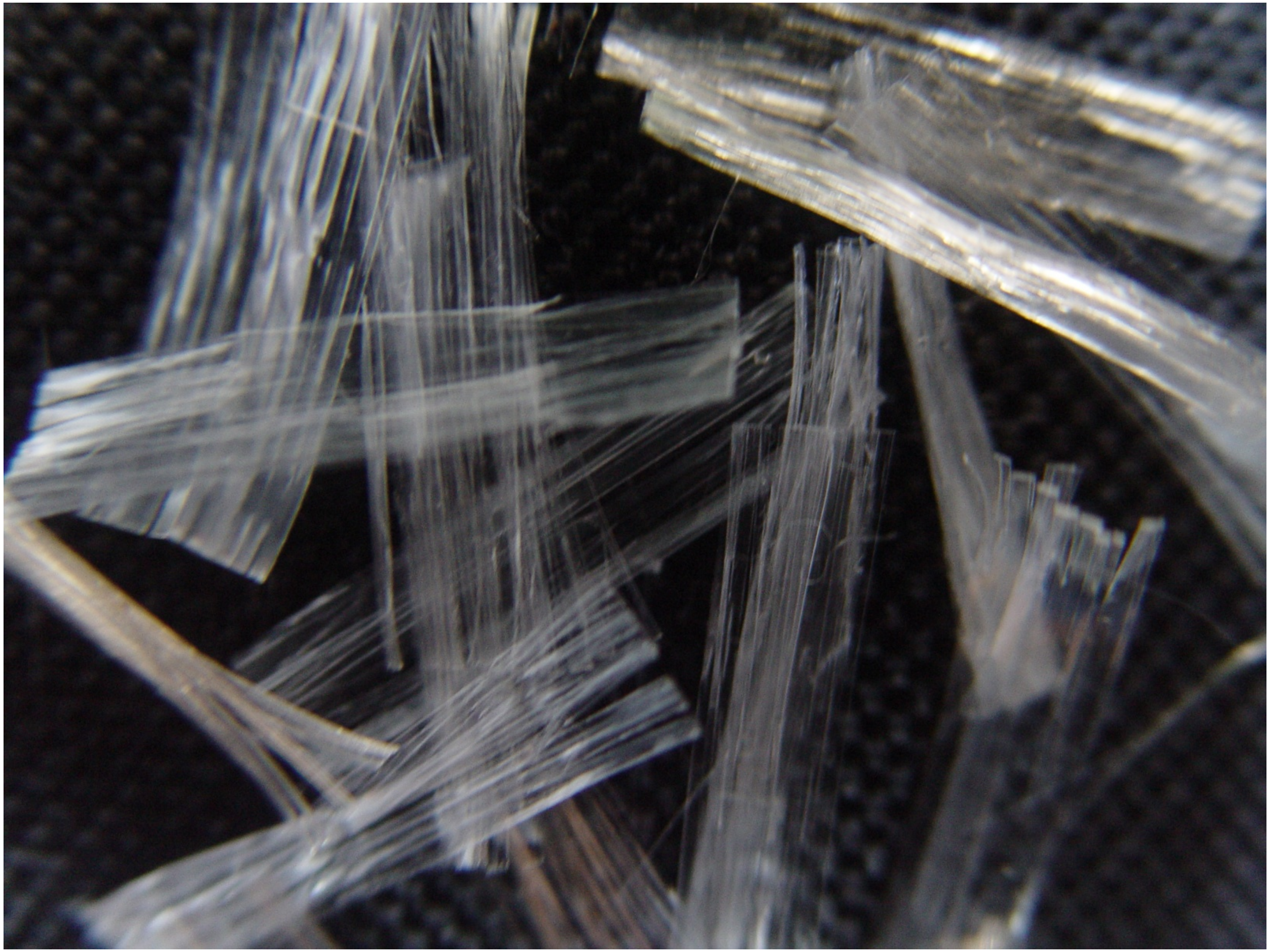
- **Typically prefabricated welded cages**
- **Durability**



Steel Fiber Reinforced Concrete

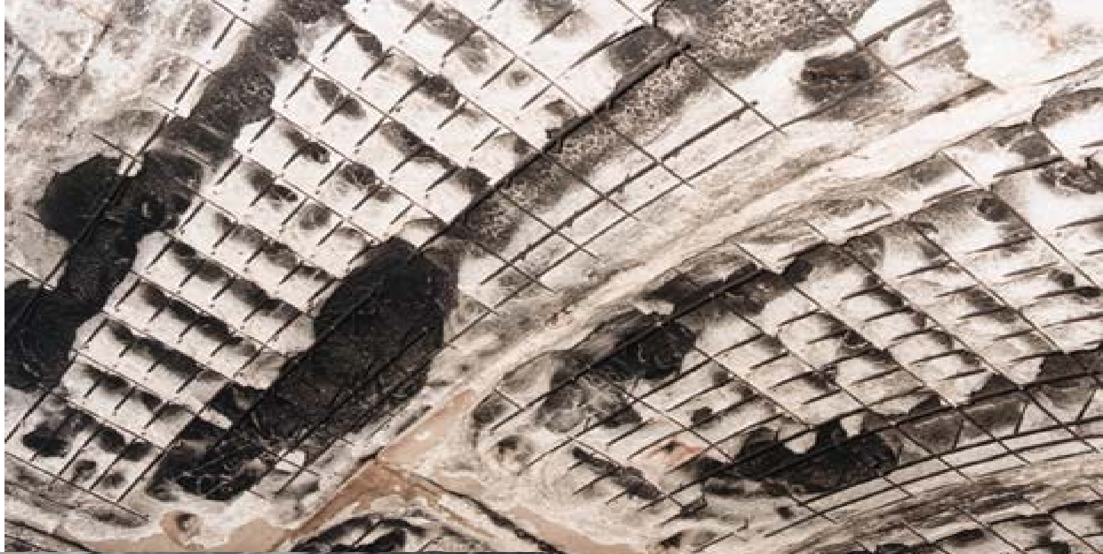
- **SFRC provides increased durability, simpler manufacturing and cost savings**
- **Surface Finish – Smooth, no exposed fibers**
- **Repairs – no corrosion protection required**

Polypropylene Fibers

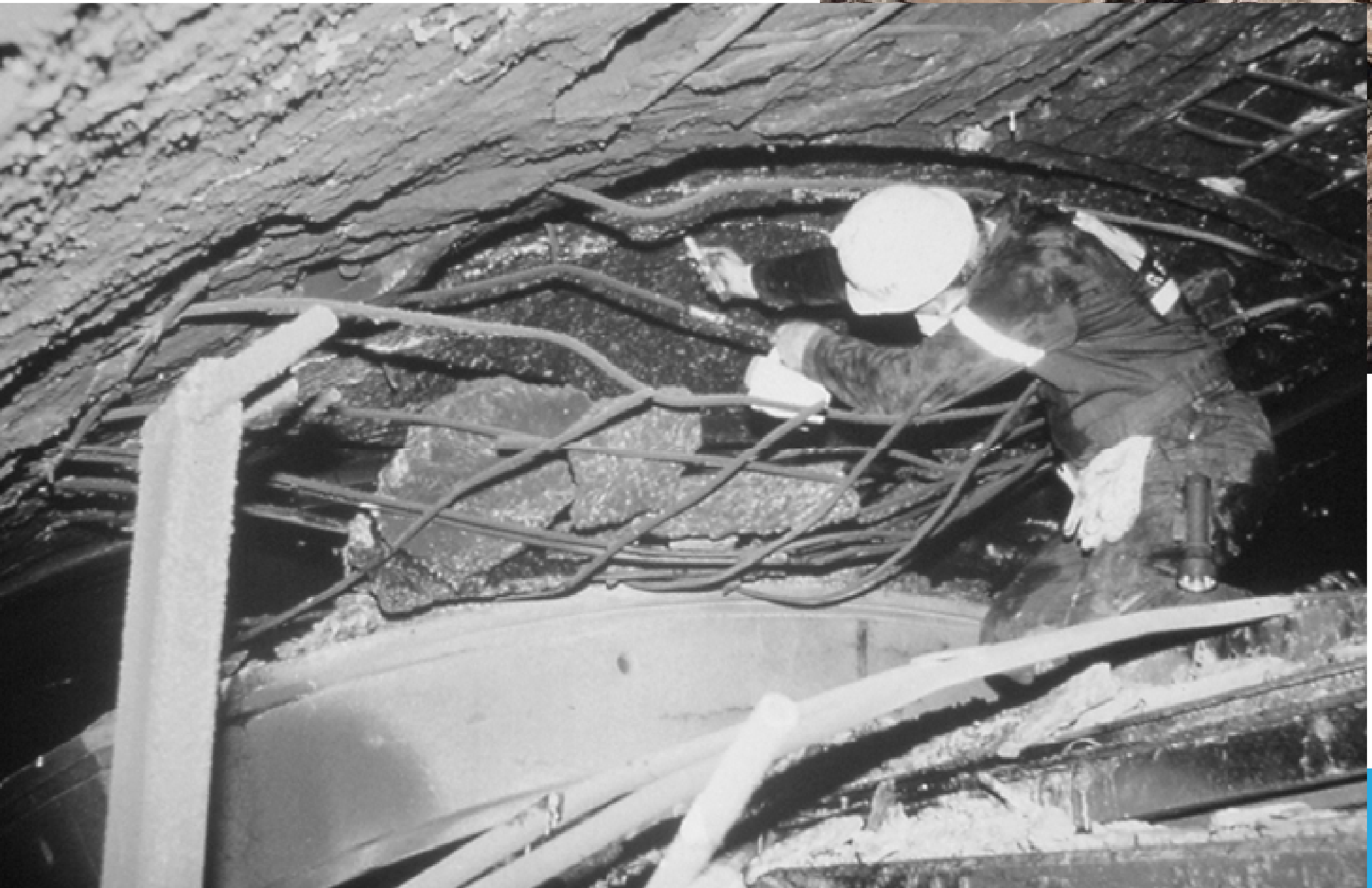


Fire Damage

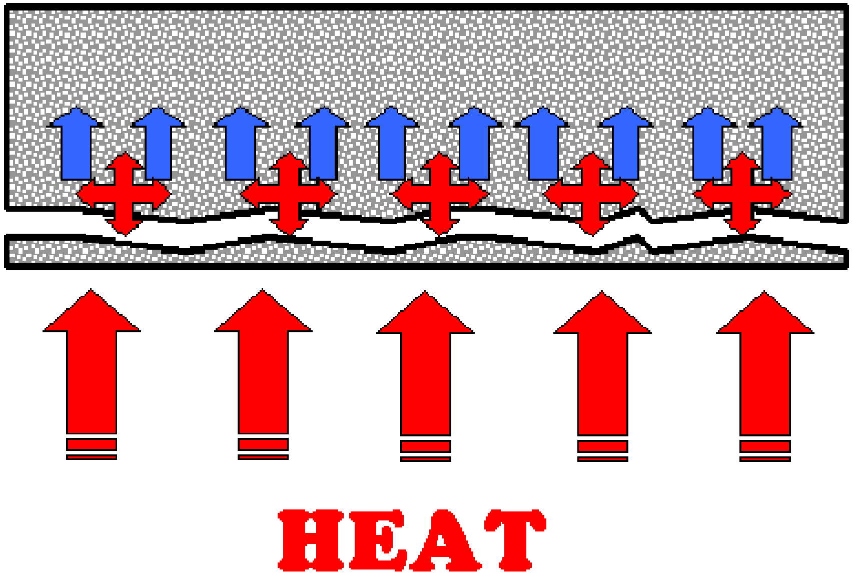
Channel Tunnel



Storebelt



‘Normal’ Concrete

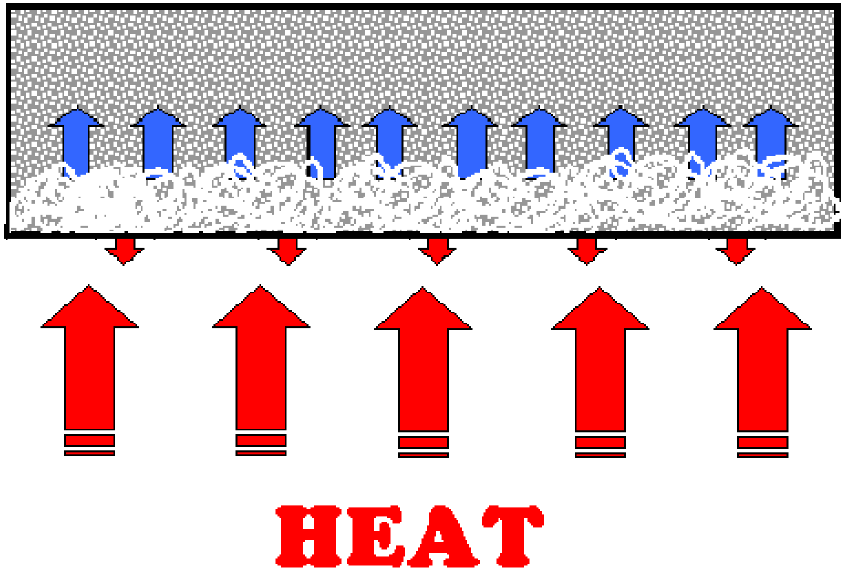


1. Moisture moves away from heat front

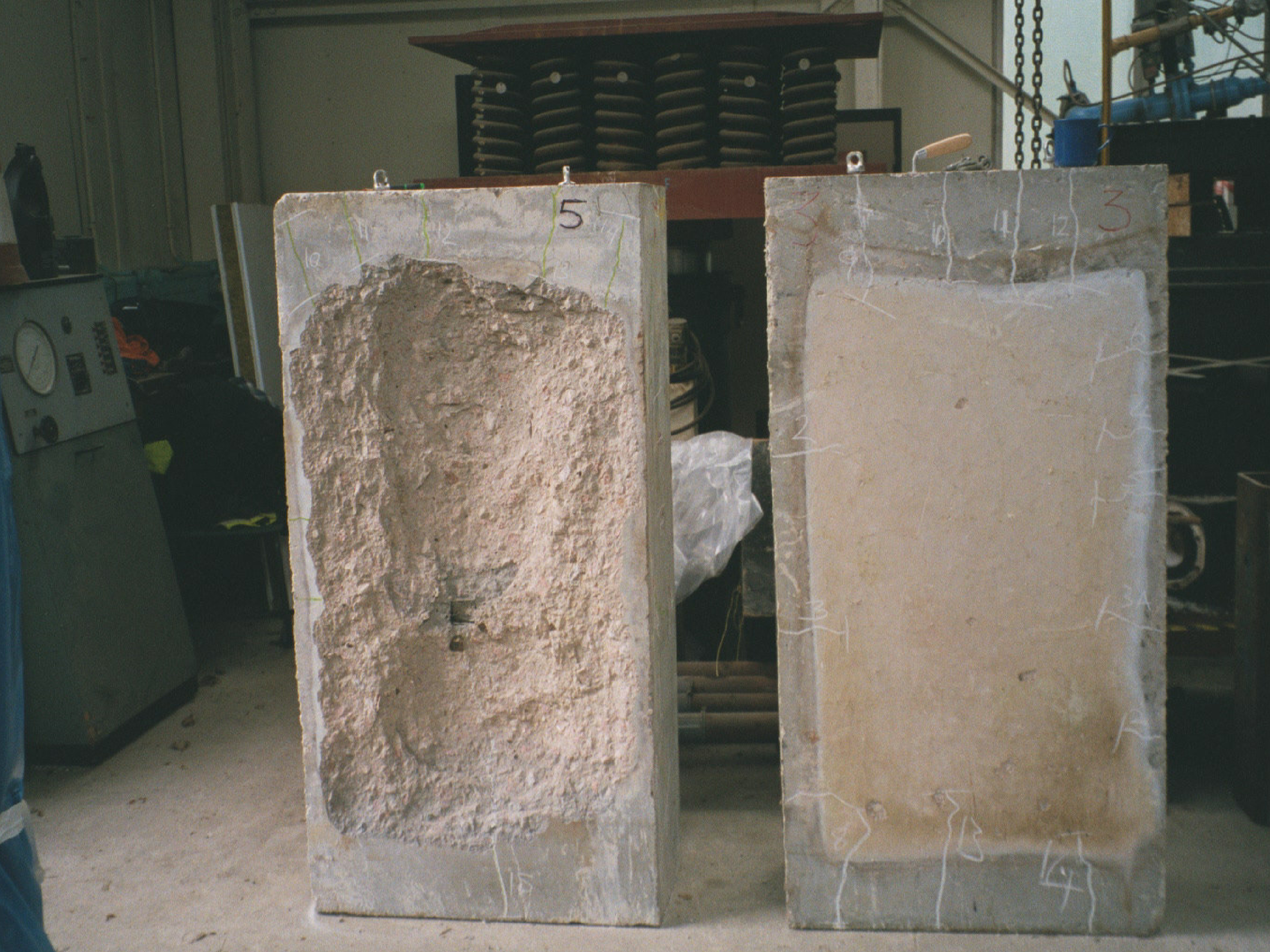
2. Vapour pressure increases as heat front advances

3. Vapour pressure > tensile strength of concrete and explosive spalling occurs

With Polypropylene Fibers



2. Fibres melt at 160° C form interconnecting passages for vapour pressure to escape


5
10
11
12
15
3
10
11
12
3
14

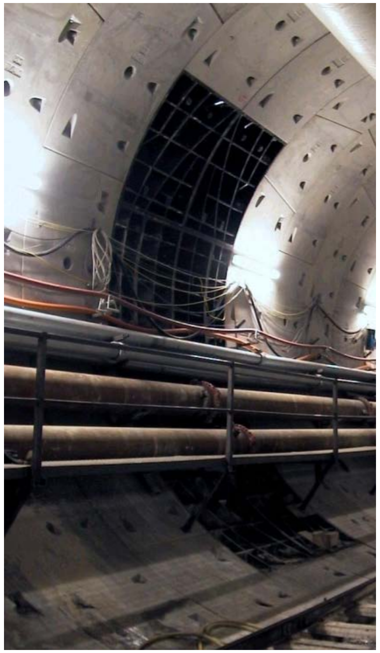
Resistance to Hydrogen Sulphide attack

- **Polymer Concrete**

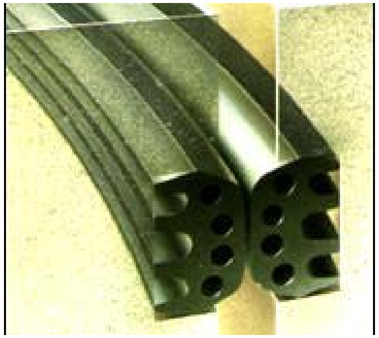
- **Integral GRP liners**

Steel/SGI Linings

- Suitable for high load locations – eg openings.
- Steel – fabricated; Spheroidal Graphite Iron - cast



Fixings and Appurtenances



EPDM/ Hydrophilic Gaskets

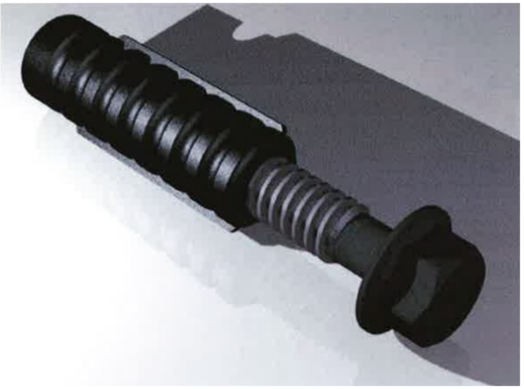
Bolts and Bolt Inserts

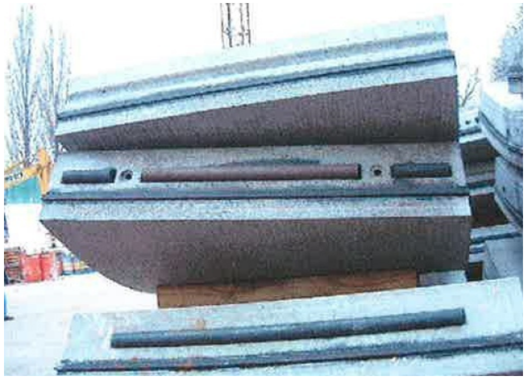
Alignment Dowels

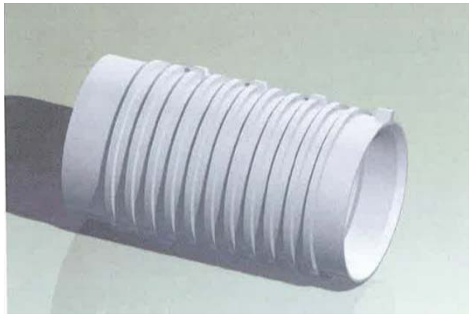
Alignment Balls

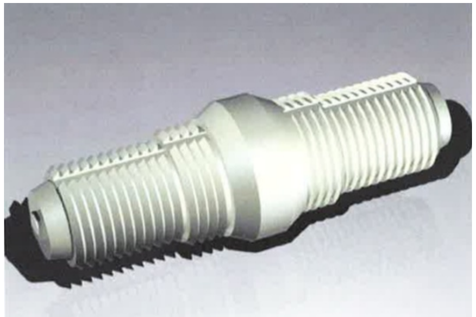
Guide Rods

Lifting Sockets



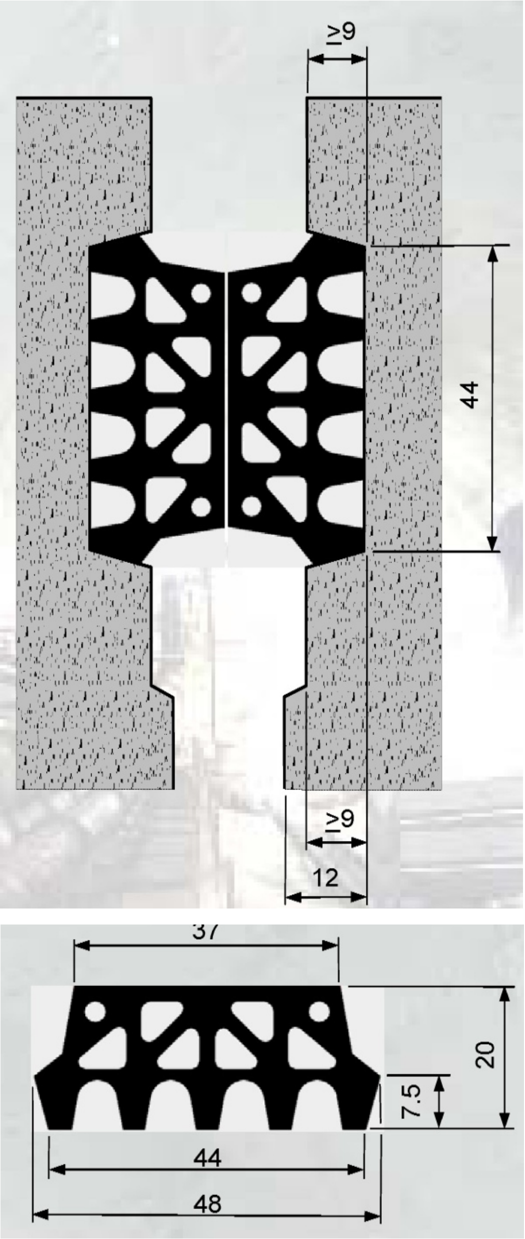




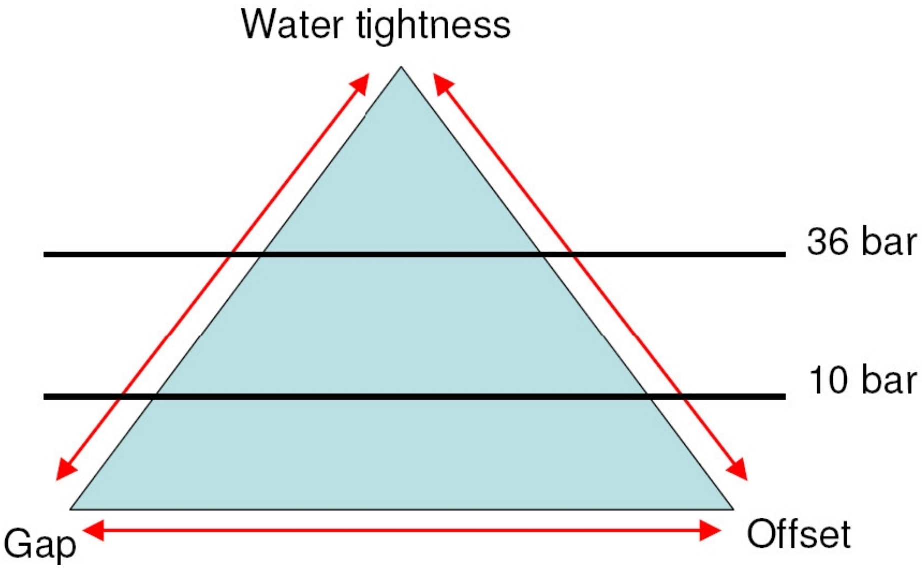


EPDM Gasket

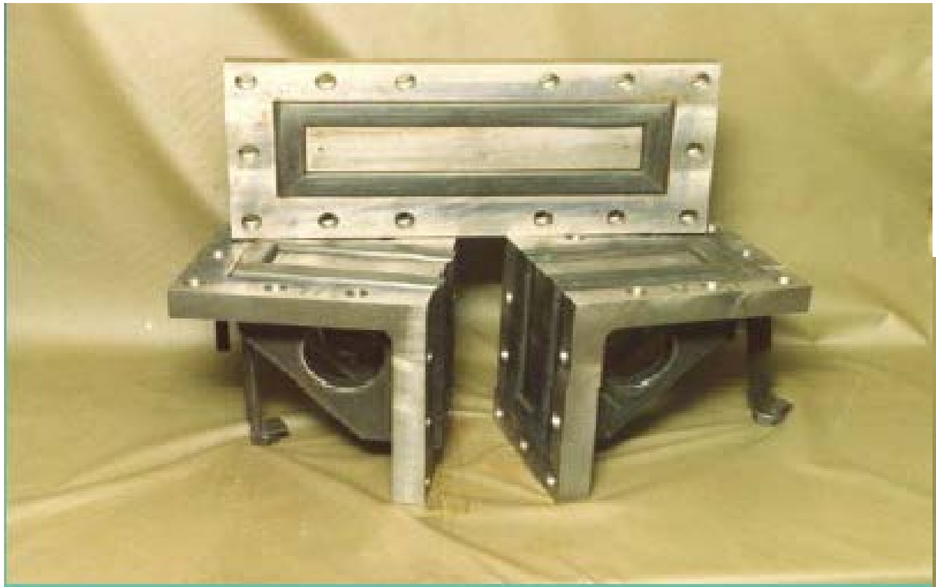
- **Gaskets compressed against each other when lining is erected and provide sealing against water ingress**
- **Design for range of segment offsets and gaps**



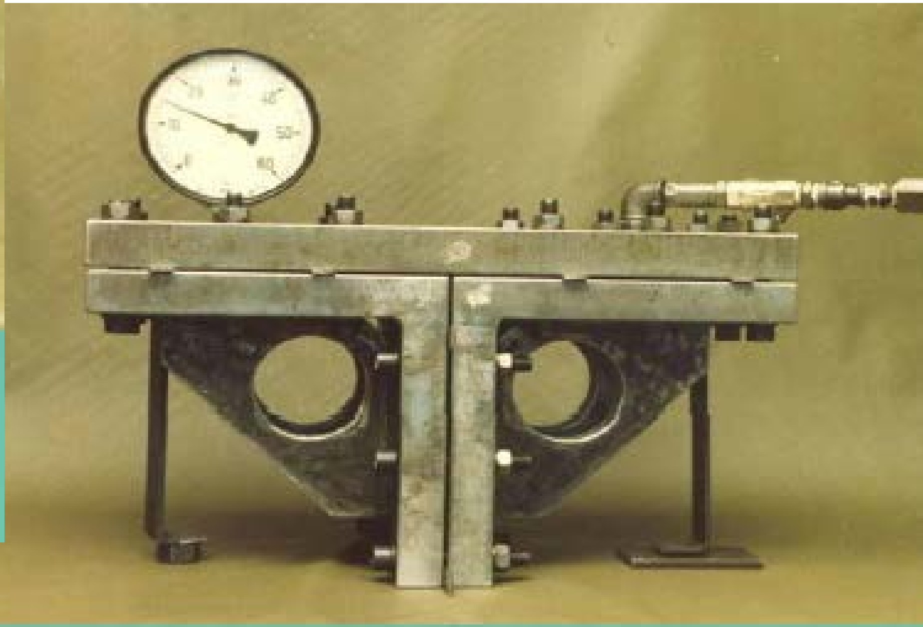
Triangle of gasket performance:



EPDM Gasket Testing



T-Joint Test Rig
open

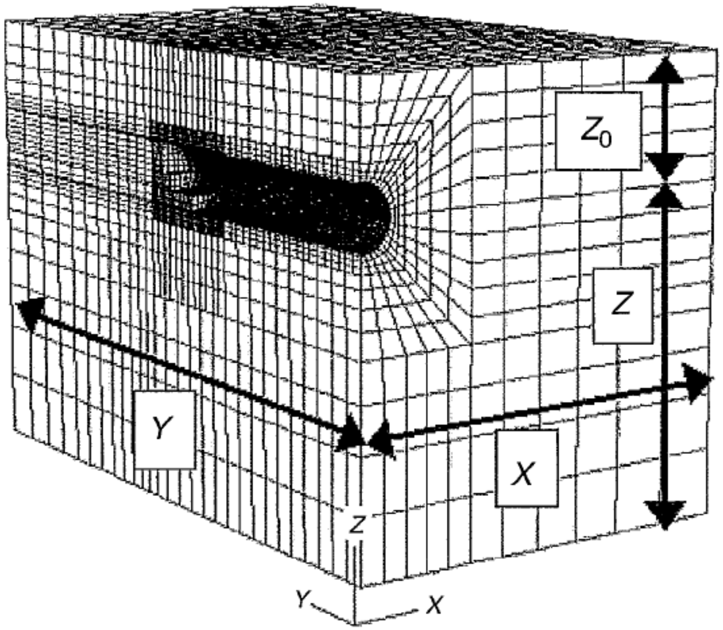


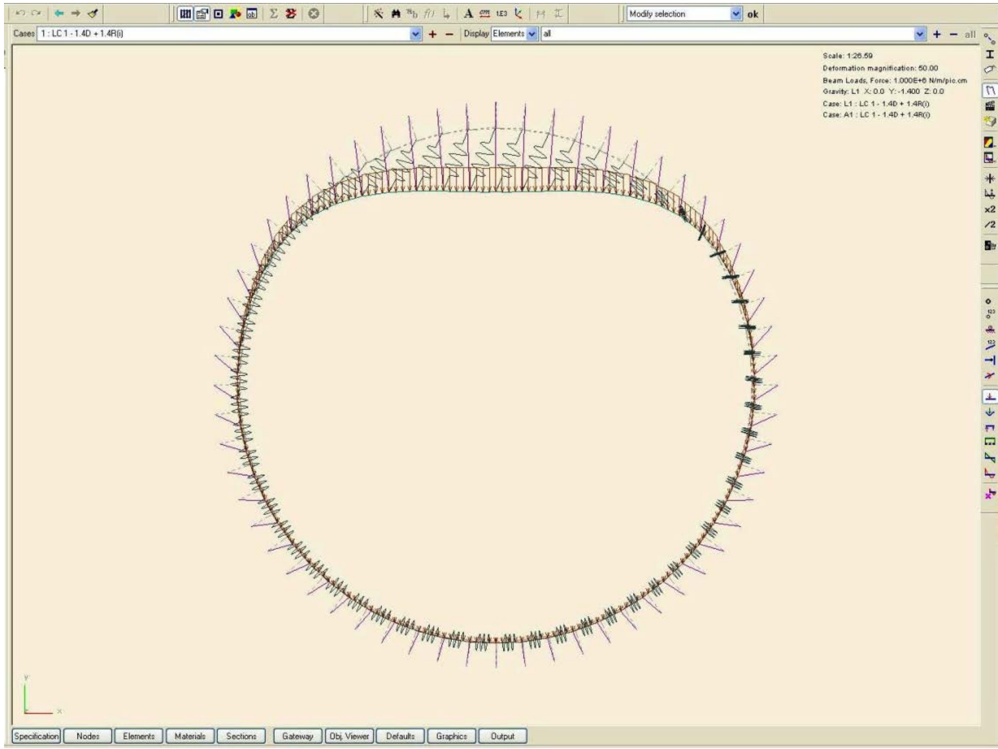
T-Joint Test Rig
closed

Ring Design

- **Continuum Analysis Models**
- **Bedded beam-spring**
- **Distortion Ratio**
- **Numerical Analysis**

From Einstein & Schwartz (1979)	**Full Slip** (no shear stress transmission)	**No Slip** (no relative shear displacement)
Compressibility ratio, **C*** / Flexibility ratio, **F***	$C^* = \frac{E_c R(1-\nu_s^2)}{EA(1-\nu^2)}$ / $F^* = \frac{E_c R^3(1-\nu_s^2)}{EI(1-\nu^2)}$	
Internal support forces, **M & N**	$\frac{M}{P_v R^2} = \frac{1}{2}(1-k_0)(1-2a_2^*)\cos 2\theta$	$\frac{M}{P_v R^2} = \frac{1}{4}(1-k_0)(1-2a_2^* + 2b_2^*)\cos 2\theta$
	$\frac{N}{P_v R} = \frac{1}{2}(1+k_0)(1-a_0^*)$ $+\frac{1}{2}(1+k_0)(1-2a_2^*)\cos 2\theta$	$\frac{N}{P_v R} = \frac{1}{2}(1+k_0)(1-a_0^*)$ $+\frac{1}{2}(1-k_0)(1+2a_2^*)\cos 2\theta$
where:	$a_0^* = \frac{C^* F^*(1-\nu)}{C^* + F^* + C^* F^*(1-\nu)}$ $a_2^* = \frac{(F^*+6)(1-\nu)}{2F^*(1-\nu)+6(5-6\nu)}$	$a_0^* = \frac{C^* F^*(1-\nu)}{C^* + F^* + C^* F^*(1-\nu)}$ / $a_2^* = \beta . b_2^*$ $\beta = \frac{(6+F^*)C^*(1-\nu)+2F^*\nu}{3F^* + 3C^* + 2C^* F^*(1-\nu)}$ $b_2^* = \frac{C^*(1-\nu)}{2[C^*(1-\nu)+4\nu-6\beta-3\beta C^*(1-\nu)]}$



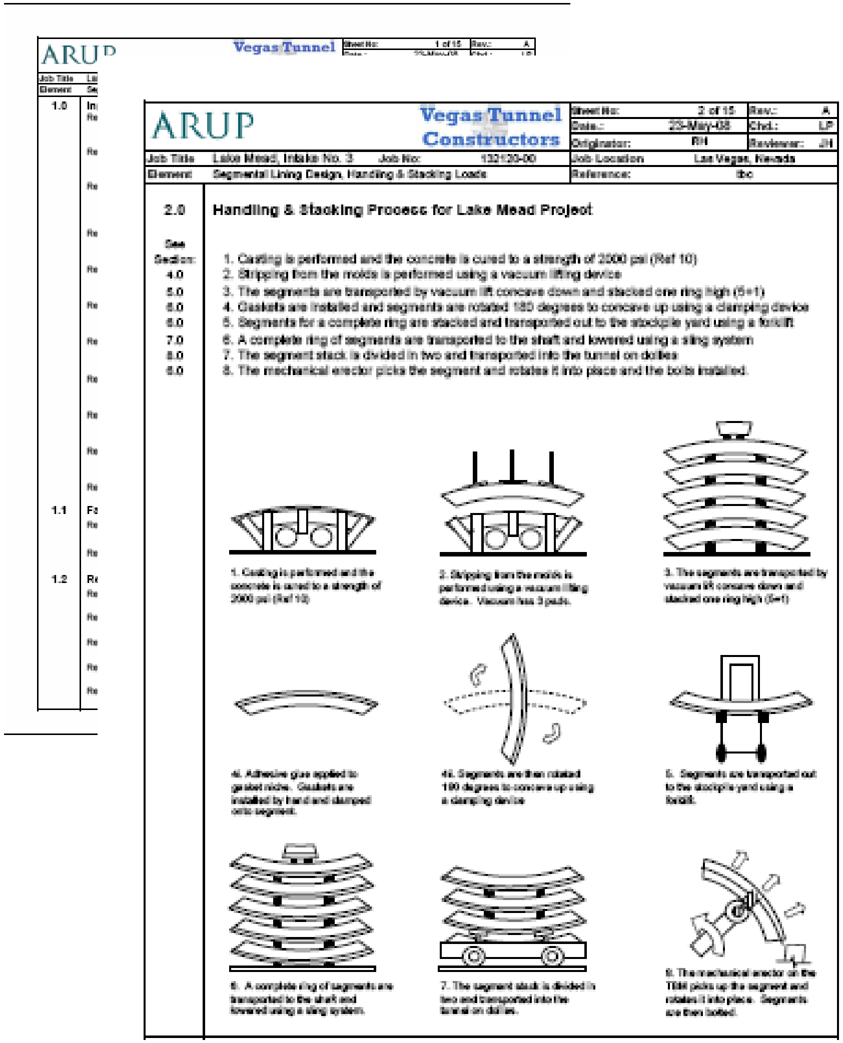

Cases 1 : LC 1 - 1.4D + 1.4R(i)

Display Elements all

Modify selection ok

Scale: 1:26.59
Deformation magnification: 50.00
Beam Loads, Force: 1.000E+6 N/m/pic.cm
Gravity: L1 X: 0.0 Y: -1.400 Z: 0.0
Case: L1 : LC 1 - 1.4D + 1.4R(i)
Case: A1 : LC 1 - 1.4D + 1.4R(i)

Segment Design – Manufacture and Handling



ARUP	Vegas Tunnel Constructors	Sheet No:	2 of 15	Rev.:	A
		Date.:	23-May-08	Chd.:	LP
		Originator:	RH	Reviewer:	JH
Job Title	Lake Mead, Intake No. 3 Job No: 132130-00	Job Location	Las Vegas, Nevada		
Element	Segmental Lining Design, Handling & Stacking Loads	Reference:	tbc		

2.0 Handling & Stacking Process for Lake Mead Project

See Section:

4.0 1. Casting is performed and the concrete is cured to a strength of 2000 psi (Ref 10)
5.0 2. Stripping from the molds is performed using a vacuum lifting device
6.0 3. The segments are transported by vacuum lift concave down and stacked one ring high (5+1)
6.0 4. Gaskets are installed and segments are rotated 180 degrees to concave up using a clamping device
6.0 5. Segments for a complete ring are stacked and transported out to the stockpile yard using a forklift
7.0 6. A complete ring of segments are transported to the shaft and lowered using a sling system
8.0 7. The segment stack is divided in two and transported into the tunnel on dollies
9.0 8. The mechanical erector picks the segment and rotates it into place and the bolts installed.

1. Casting is performed and the concrete is cured to a strength of 2000 psi (Ref 10)

2. Stripping from the molds is performed using a vacuum lifting device. Vacuum has 3 pads.

3. The segments are transported by vacuum lift concave down and stacked one ring high (5+1)

4i. Adhesive glue applied to gasket niche. Gaskets are installed by hand and clamped onto segment.

4ii. Segments are then rotated 180 degrees to concave up using a clamping device

5. Segments are transported out to the stockpile yard using a forklift.

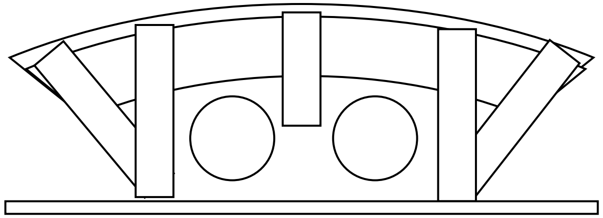
6. A complete ring of segments are transported to the shaft and lowered using a sling system.

7. The segment stack is divided in two and transported into the tunnel on dollies.

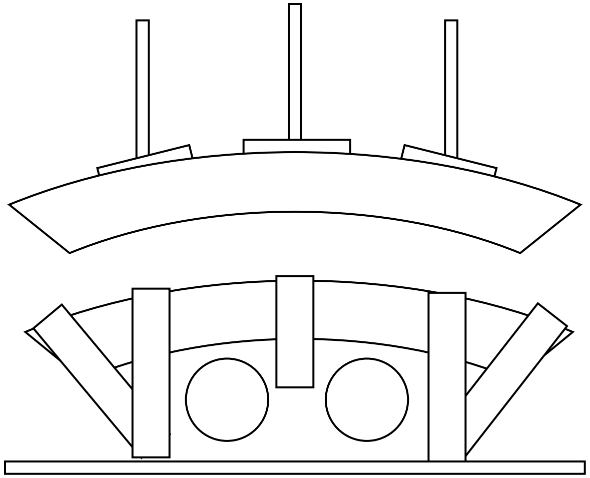
8. The mechanical erector on the TBM picks up the segment and rotates it into place. Segments are then bolted.

- Consider all load cases from initial stripping of the concrete form to erection in the tunnel

Segment Design – Manufacture and Handling

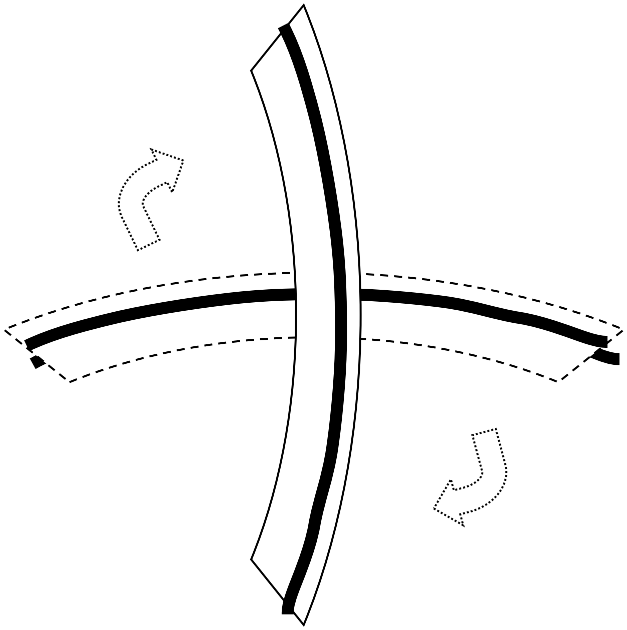


1. Segment is cast, and left in the form until the specified stripping strength is reached

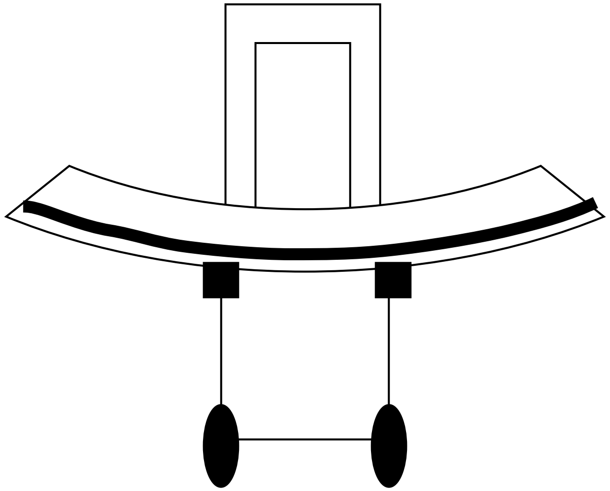


2. Segment stripped from mold – design condition depends on strength and lifting device

Segment Design – Manufacture and Handling

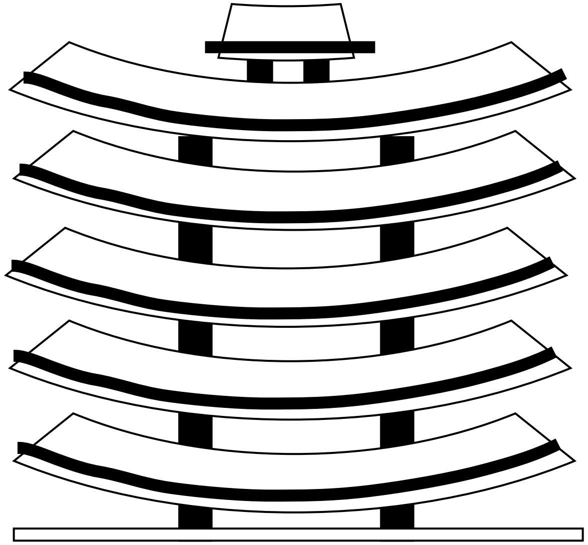


3. Segments are then rotated 180 degrees

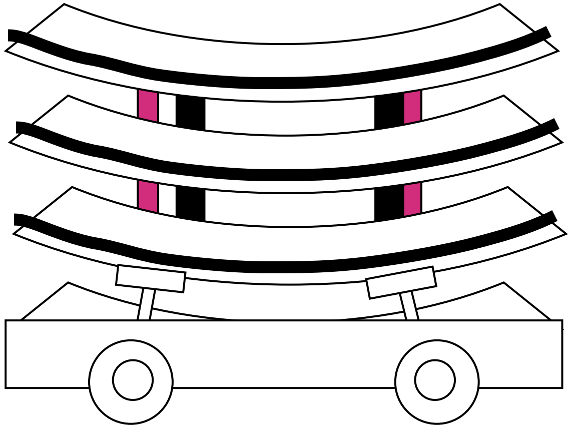


4. Segments are transported out to the stockpile yard using a forklift or gantry crane.

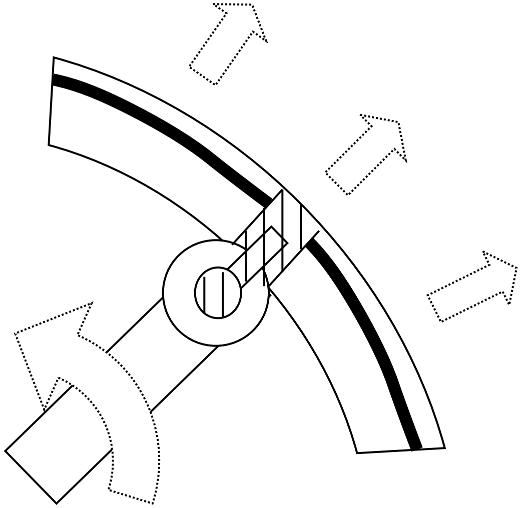
Segment Design – Manufacture and Handling



5. Segments are stacked



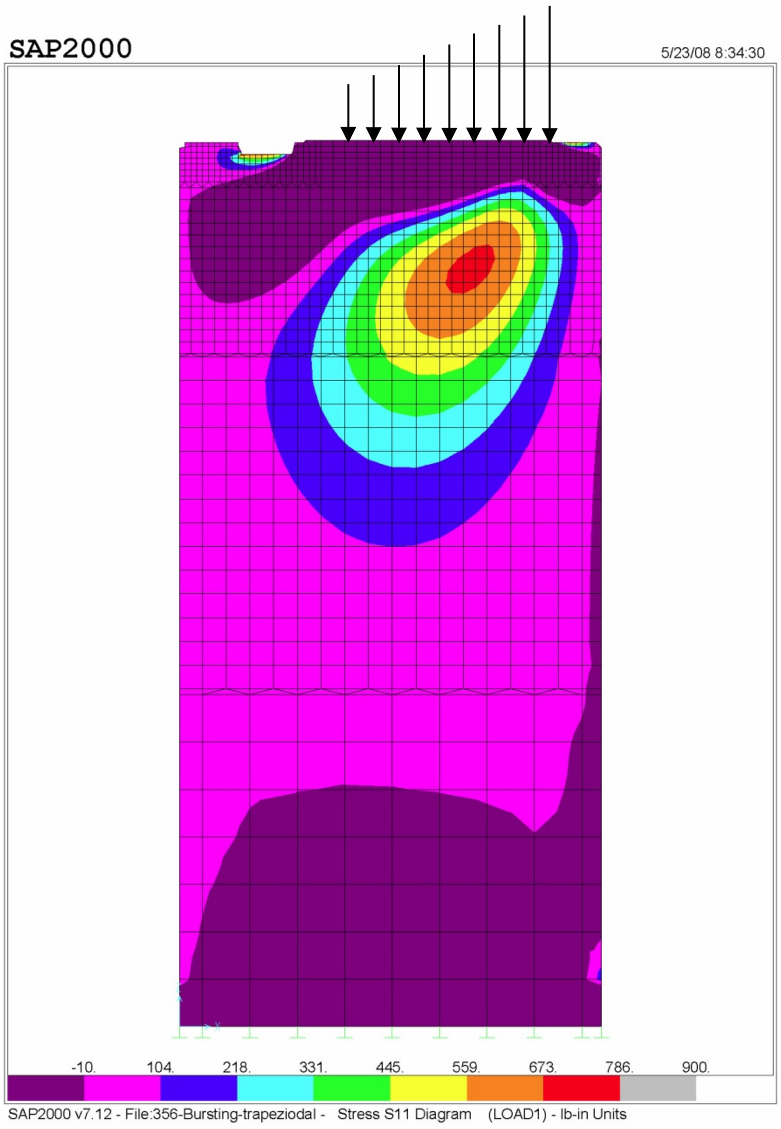
6. The segments are lifted onto the train and transported into the tunnel



7. The erector on the TBM picks up the segment & rotates it into place.

Joint Design

- Consider the impacts of poor build – not all joint surface may be in contact
- Design for bursting stresses (arrangement similar to a tensioned anchorage)
- Consider hoop loads and thrust loads from the shove rams



TEST
TEST 1
GRANITE FLAT
POCKETS FLUSH

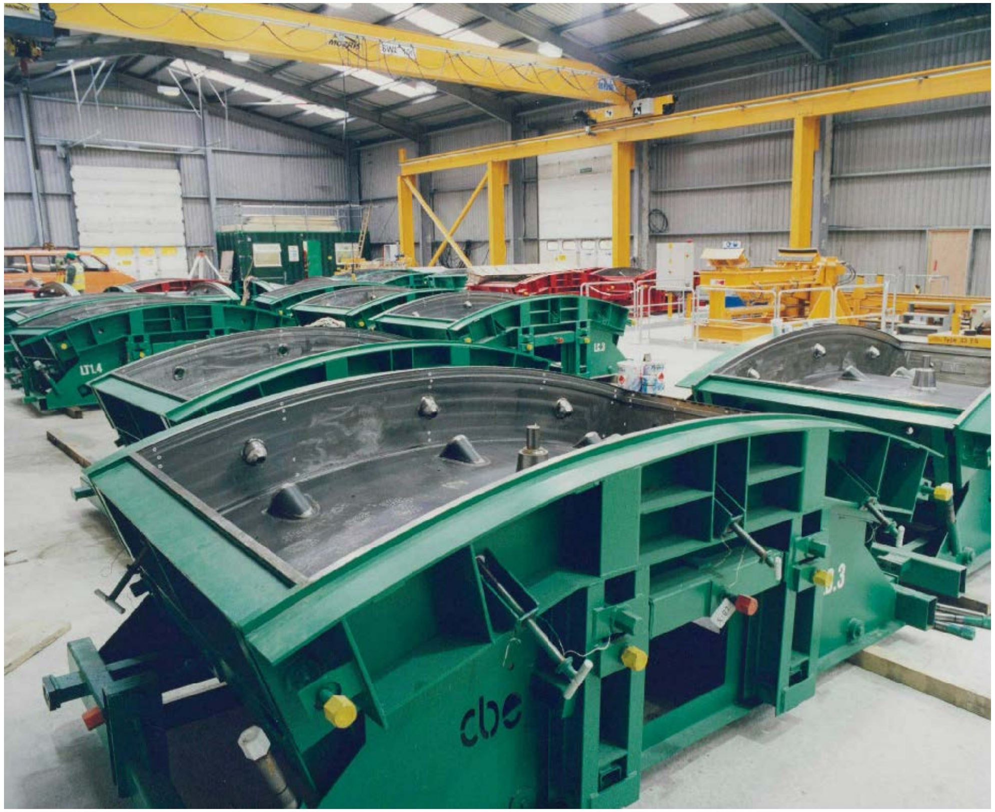
B000-3-4
8-22-02
B000-3-4
South Top
B000-3-4
South Bot
B000-3-3

Manufacture

- **Plant Types**
  - Stationary
  - Carousel

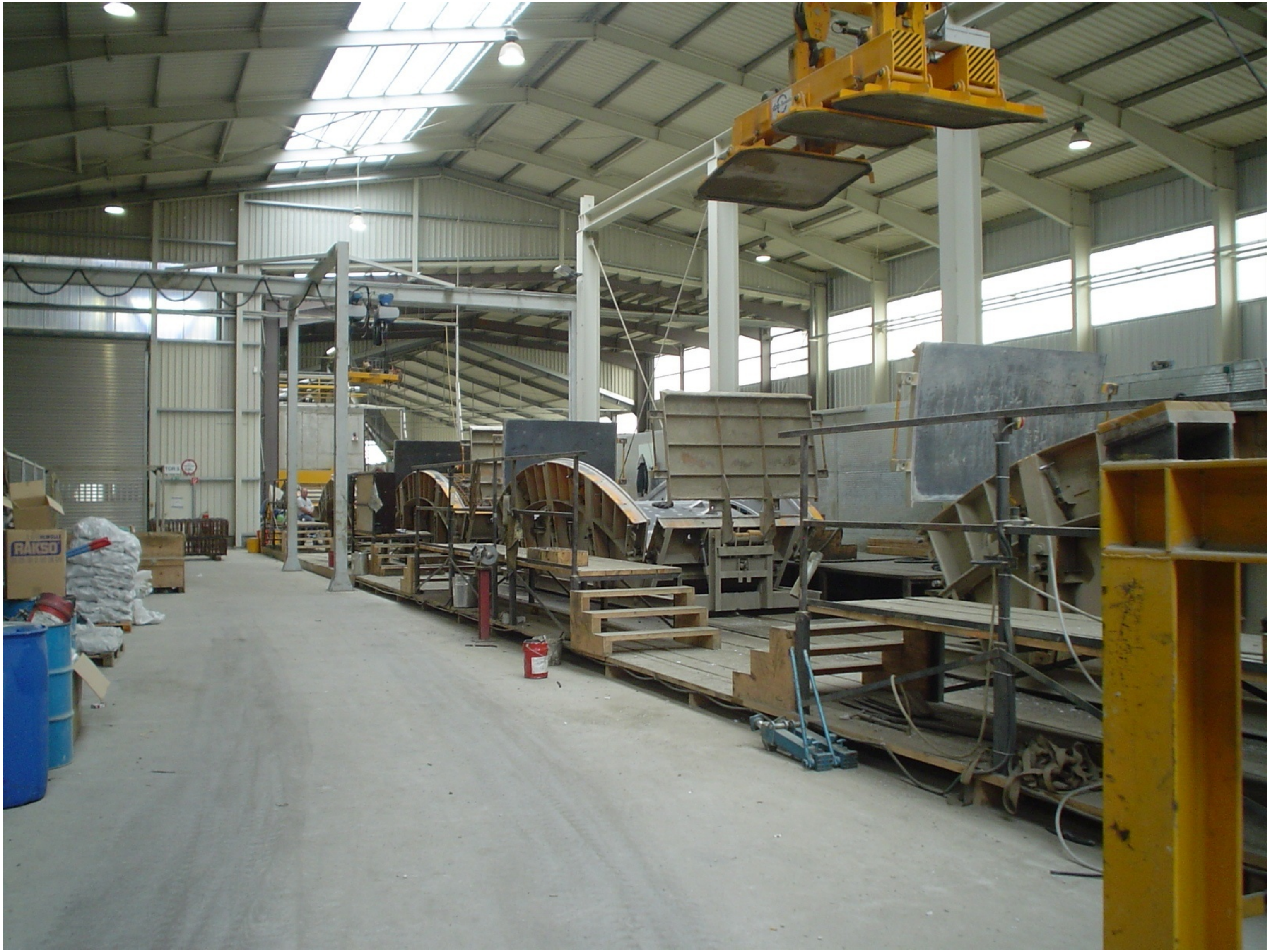
- **Plant Location**
  - Jobsite
  - Precast factory

- **Molds**
  - Horizontal
  - Vertical



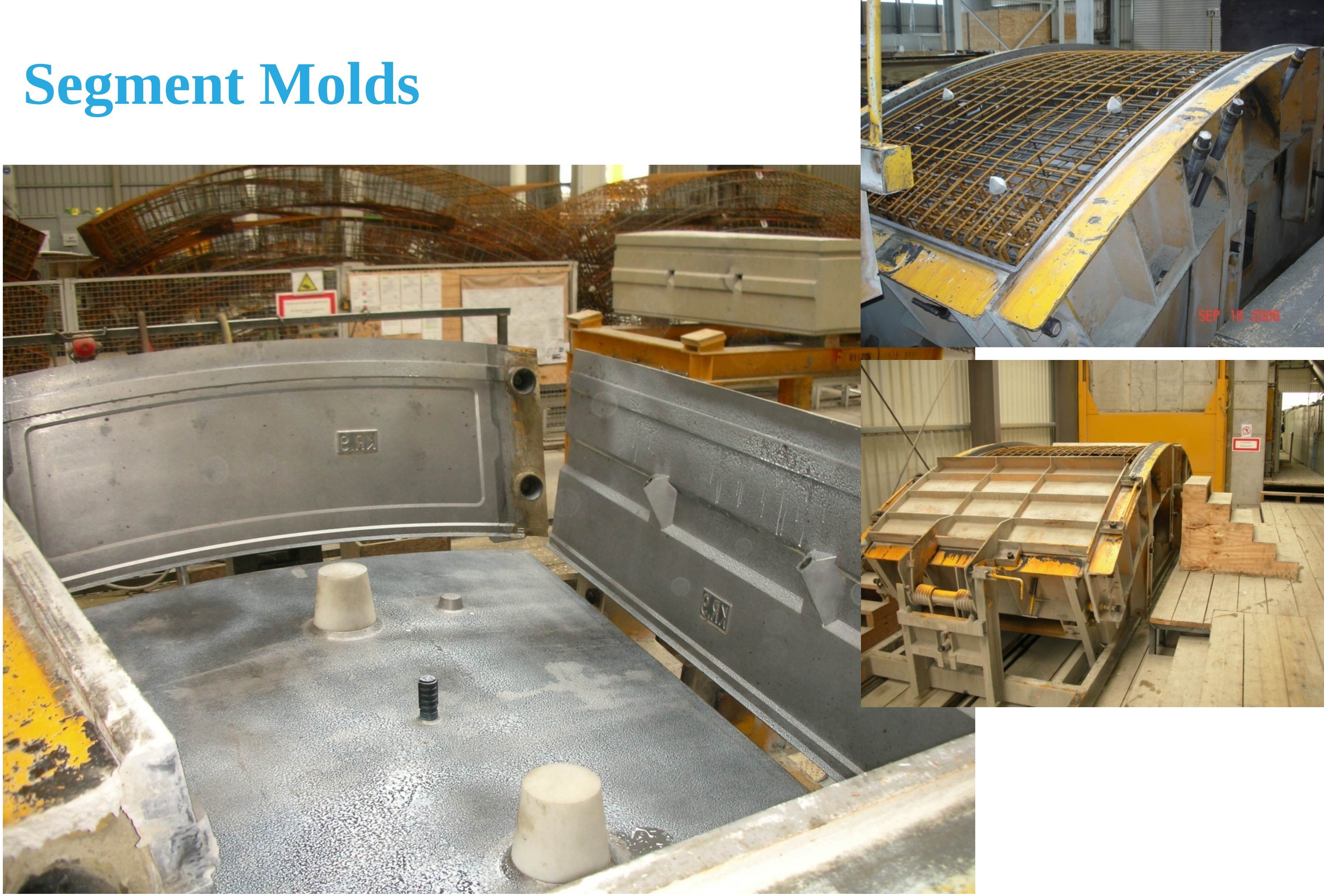
Stationary Plant

Carousel Plant



Carousel Plant

Segment Molds



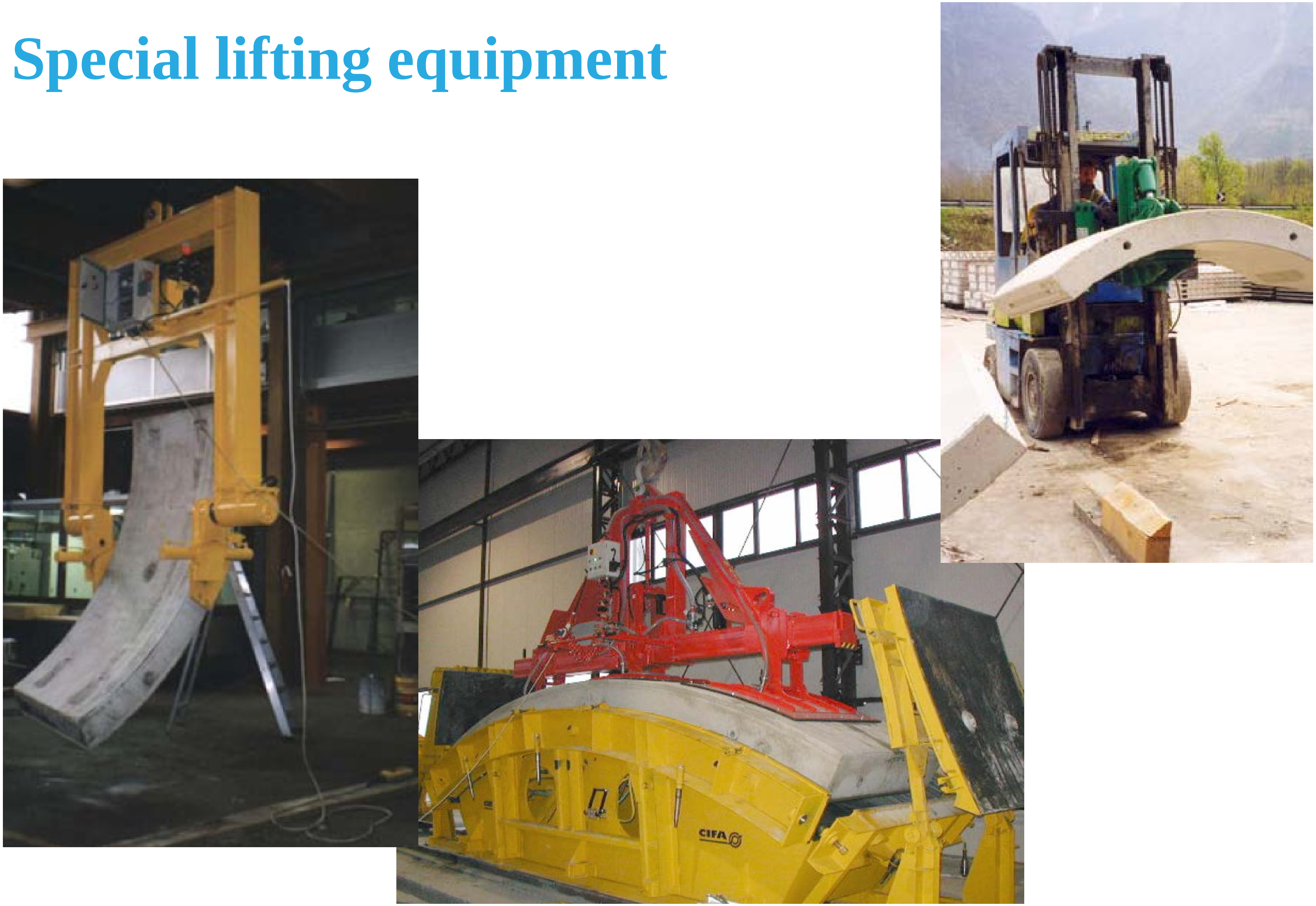
Concrete

Concrete

- **Vibration**
  - Internal pneumatic
  - External pneumatic/electric

- **Curing**
  - Steam
  - Insulation
  - Cloth

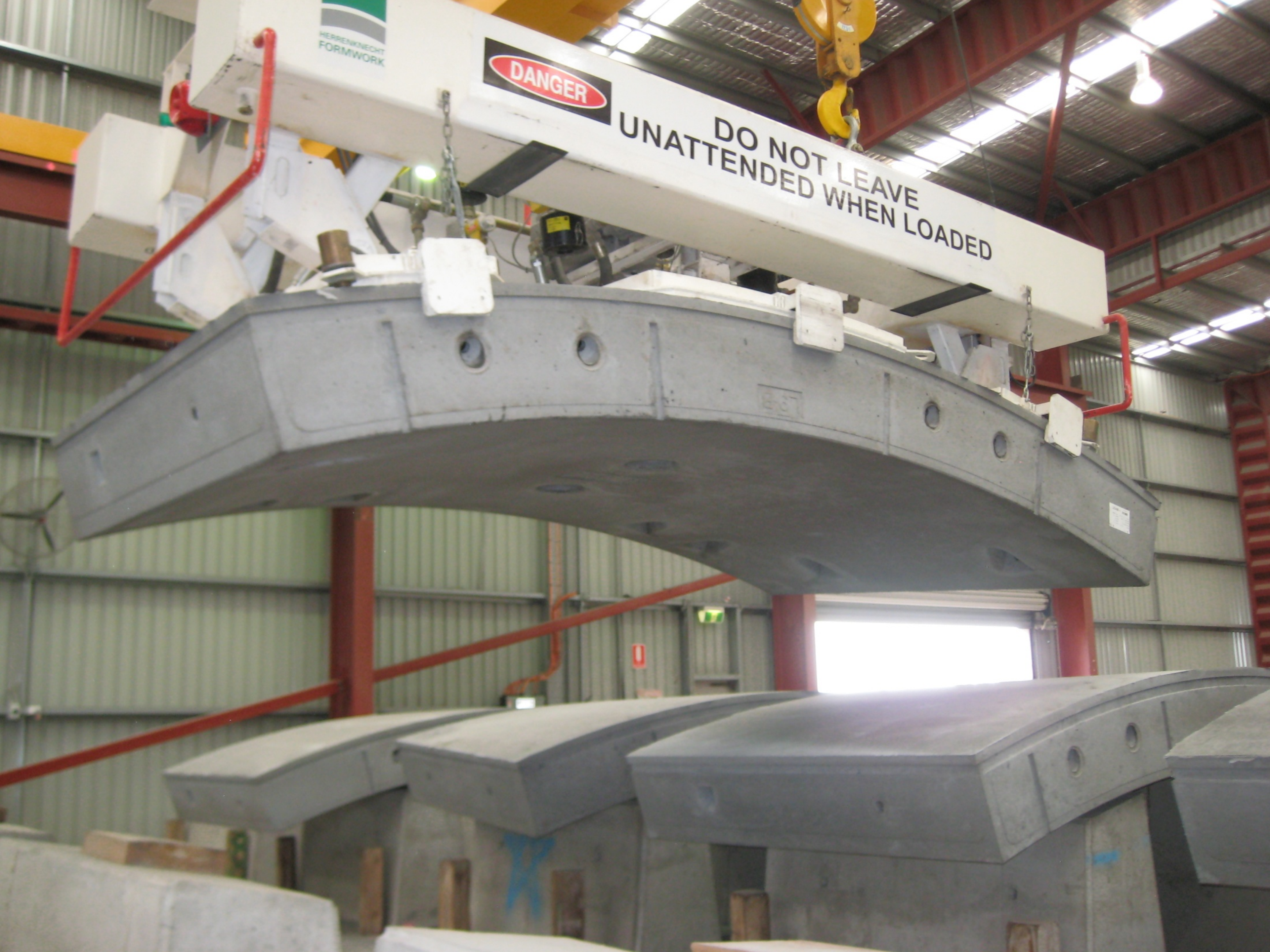
Special lifting equipment



WorkPic
call 130WORKPIC

27A
DANGER
KEEP OUT
L9C

KEEP OUT


HERRENKNECHT FORMWORK
DANGER
DO NOT LEAVE UNATTENDED WHEN LOADED

L5-B

DPR-6.5T
DPR-6.5T
BIJ27X

Demonstration Ring

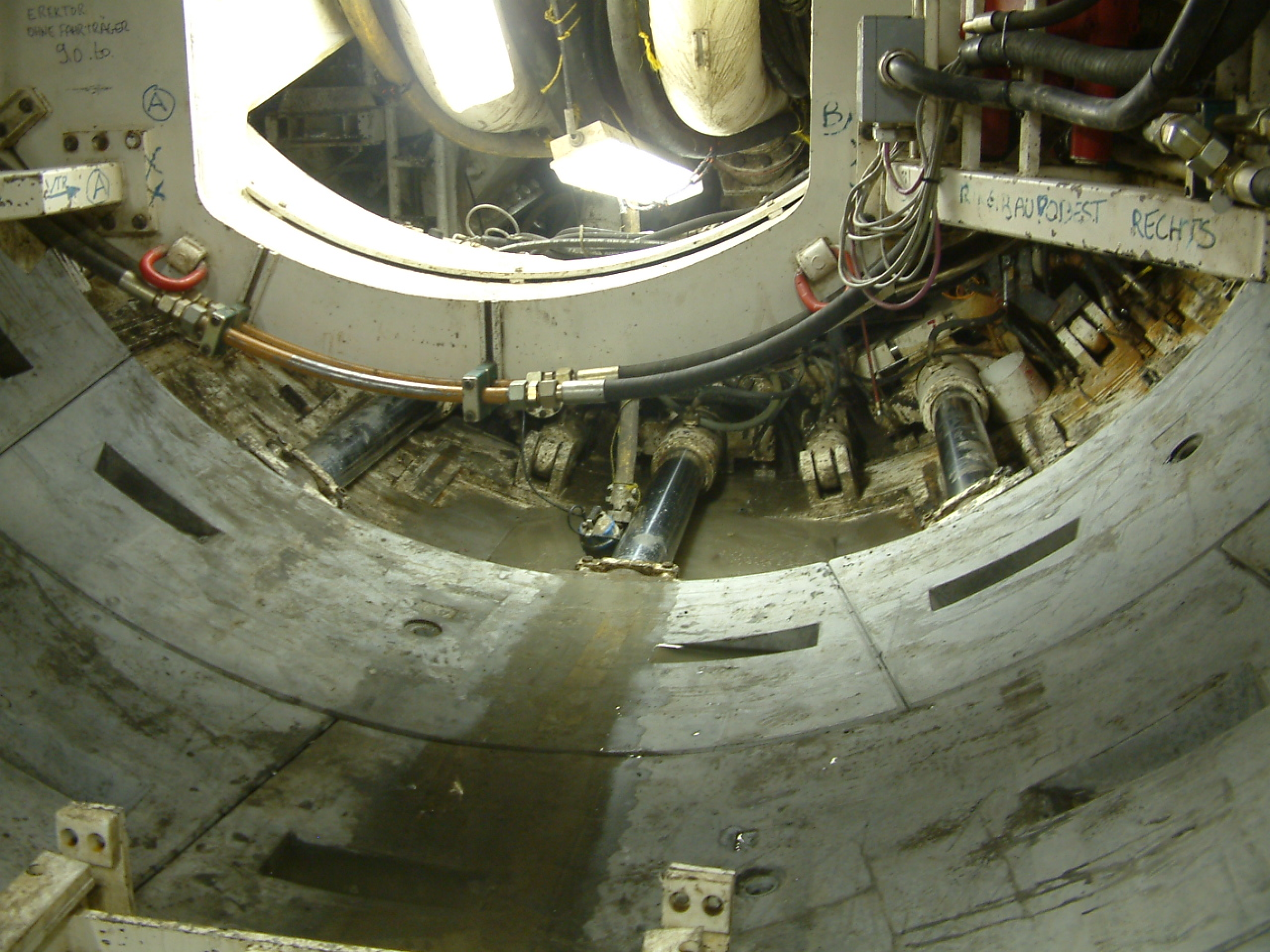
DEMAG
DEMAG
147
146

DEMAG
DEMAG

11-18-03

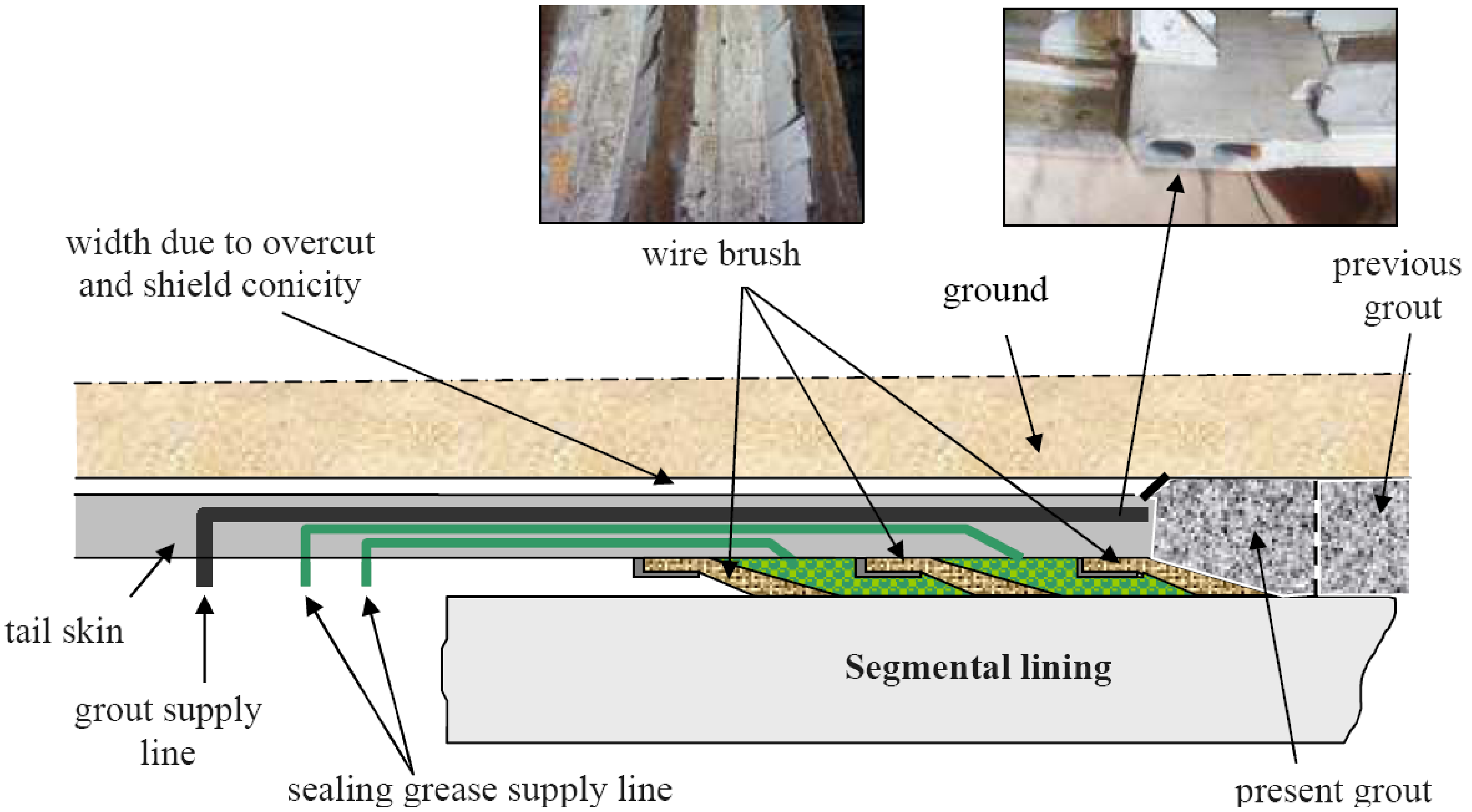
DEMAG
3,2t

THE BIG PIPE


ERKTOR
OHNE FAHRTRÄGER
9.0 to
A
A
B
RINGBAUPODEST RECHTS

Annular Grouting

- As TBM is advanced, void behind segment needs to be filled (overcut plus TBM skin thickness)
- In soft ground, essential to fill void quickly and completely to minimize settlement, and support segments
- In rock, need to support segments – but more difficult to grout
- If shunt flows are present, need to pay attention to avoid wash out.
- Secondary grouting to ensure all voids are full



width due to overcut and shield conicity

wire brush

ground

previous grout

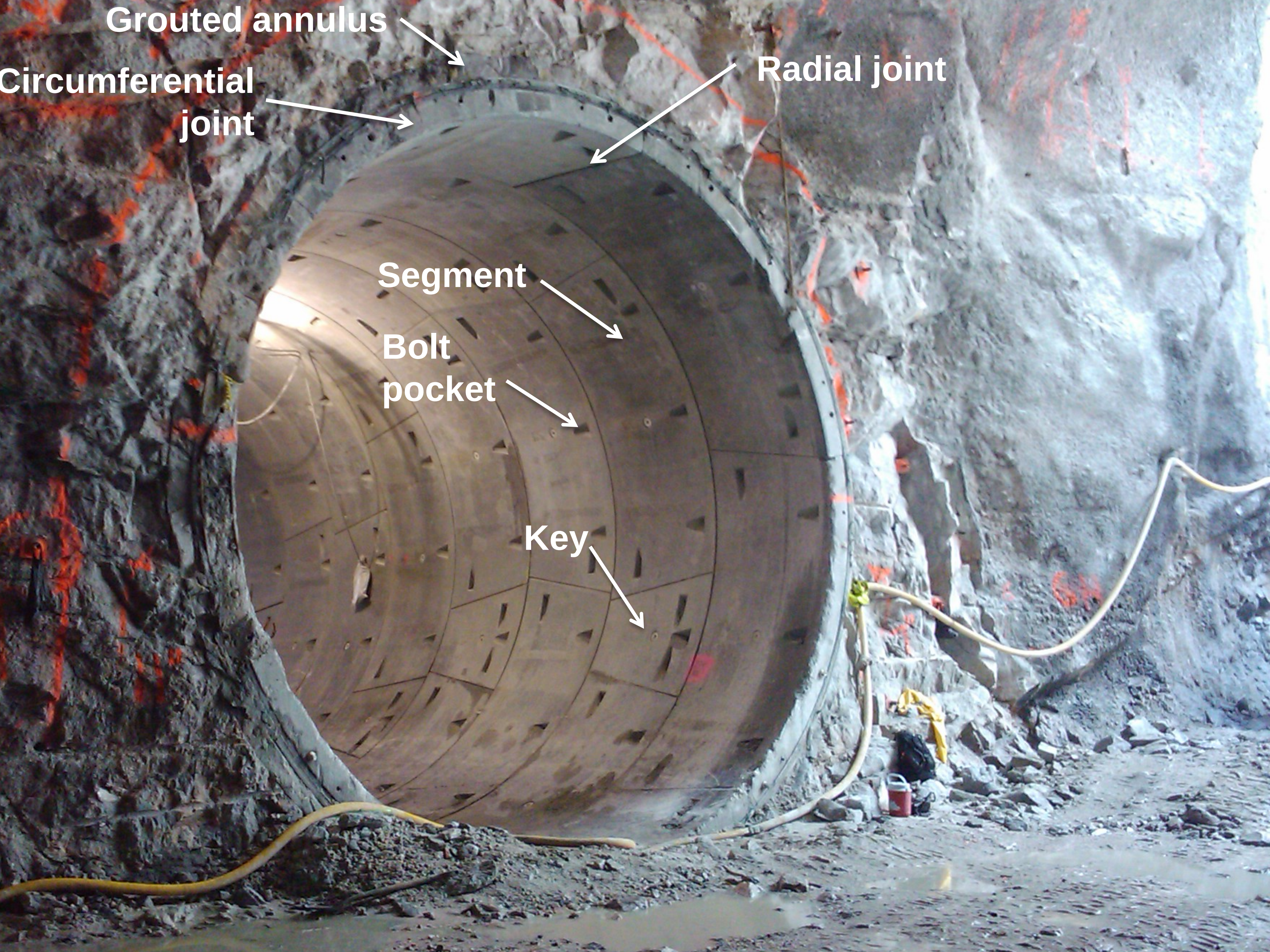
tail skin

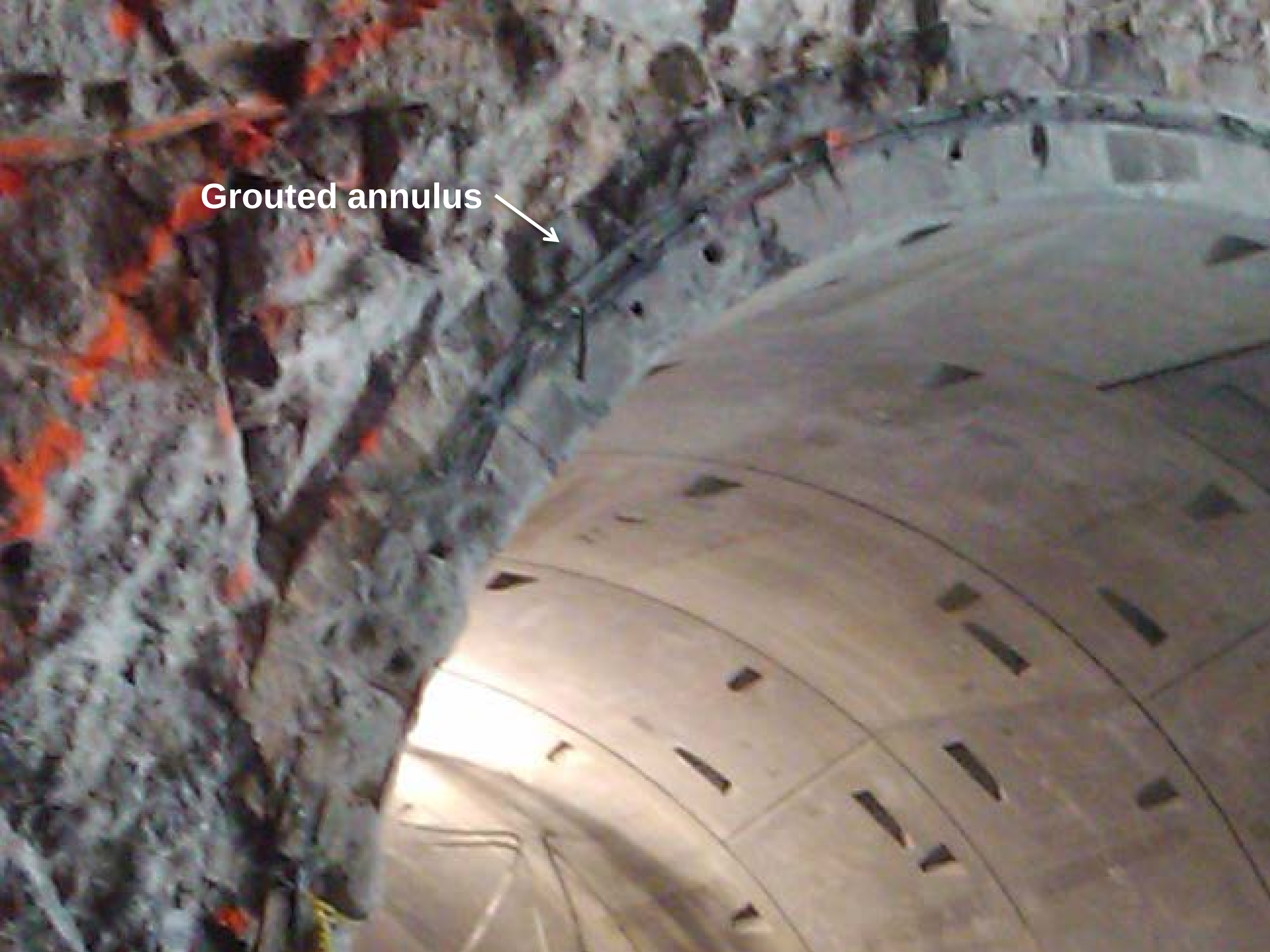
grout supply line

sealing grease supply line

Segmental lining

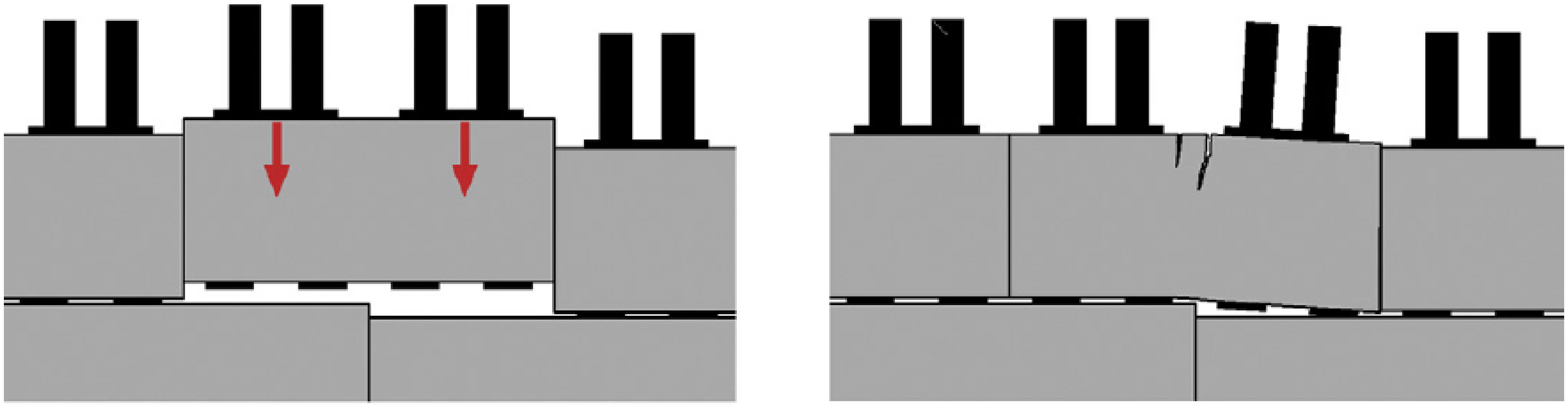
present grout


Grouted annulus
Circumferential joint
Radial joint
Segment
Bolt pocket
Key

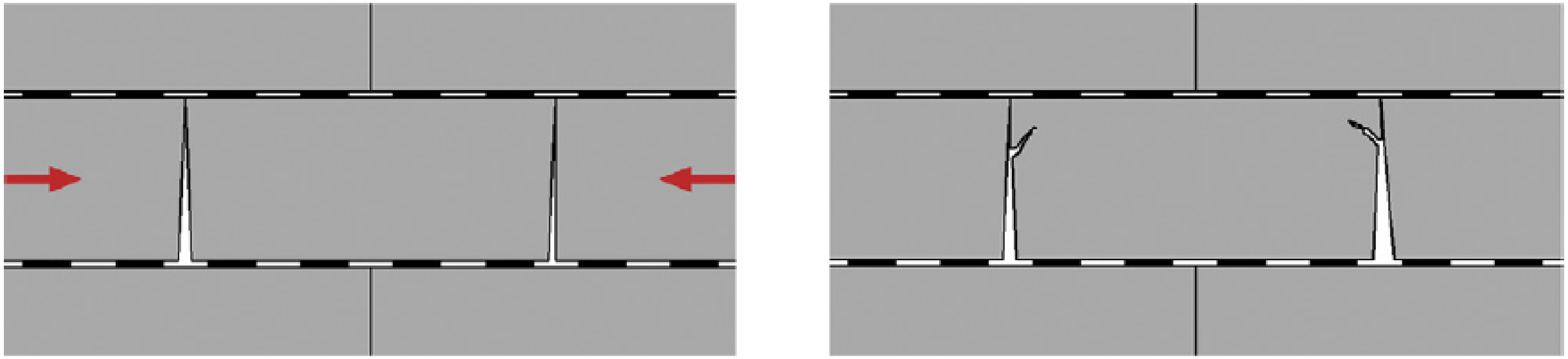

Grouted annulus

Segment Damage

S.H.P. Cavalaro et al. / Tunnelling and Underground Space Technology xxx (2011) xxx–xxx



(a) Longitudinal cracks formation



(b) Chipping of segment corner

Fig. 1. Formation of longitudinal cracks and chipping of segment corner.

Segment Damage

Table 2. Classification of segment damage during construction (JSCE, 2005, p.17)

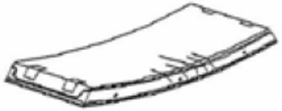
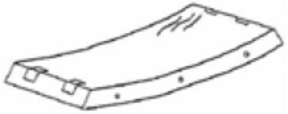
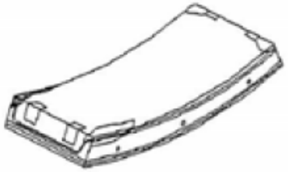
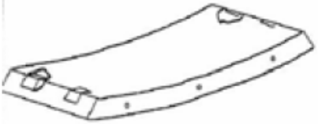
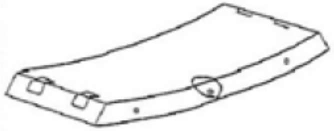
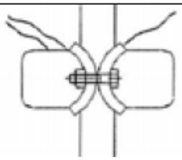
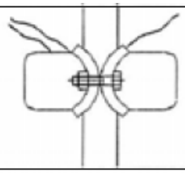
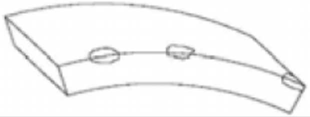
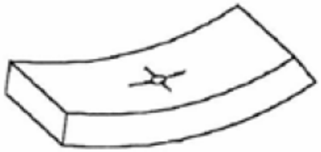
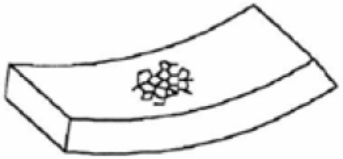
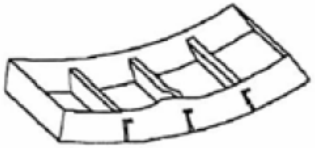
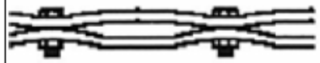
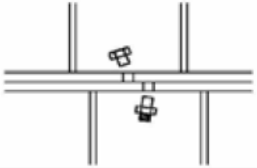
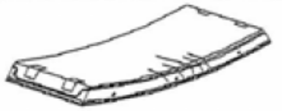
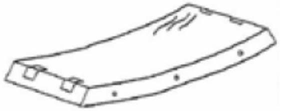
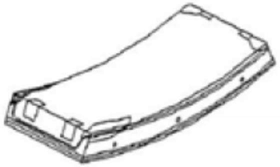
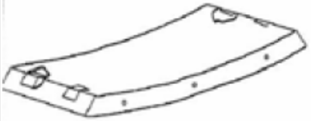
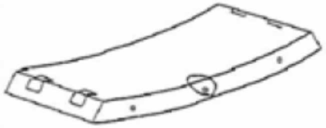
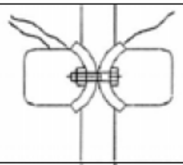
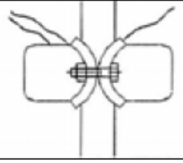
No.	Shield segment damage	Figure
1	Crack in axial dir.	
2	Crack in circumferential dir.	
3	Chipping at segment corner	
4	Stripping around segment joint	
5	Stripping around ring joint	
6	Crack/ Stripping around ring joint box	
7	Crack/ Stripping around segment joint box	
8	Stripping at outer surface	
9	Hair crack at inner surface	
10	Appearance of non-visible crack	
11	Buckling of longitudinal rib (steel segment)	
12	Deformation of rib (steel segment)	
13	Break of joint bolt	
14	Others	

Table 2. Classification of segment damage during construction (JSCE, 2005, p.17)

No.	Shield segment damage	Figure
1	Crack in axial dir.	
2	Crack in circumferential dir.	
3	Chipping at segment corner	
4	Stripping around segment joint	
5	Stripping around ring joint	
6	Crack/ Stripping around ring joint box	
7	Crack/ Stripping around segment joint box	

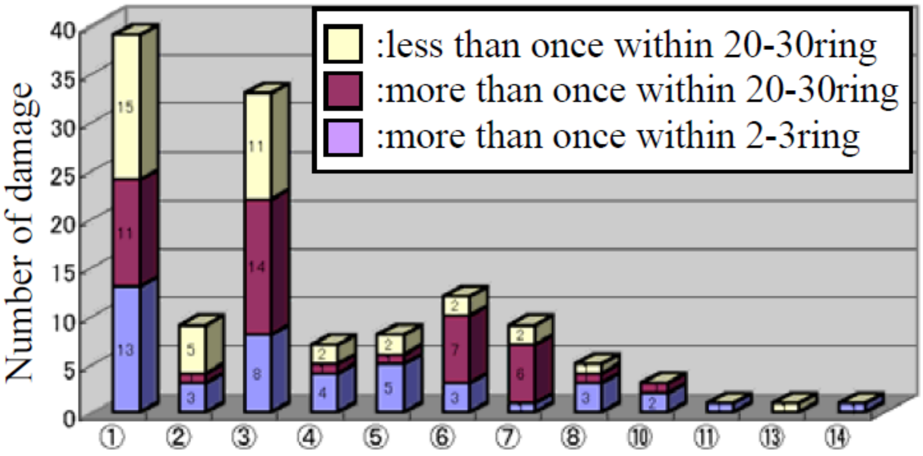


Figure 1. Frequency of segment damage during construction (JSCE, 2005, p.17)

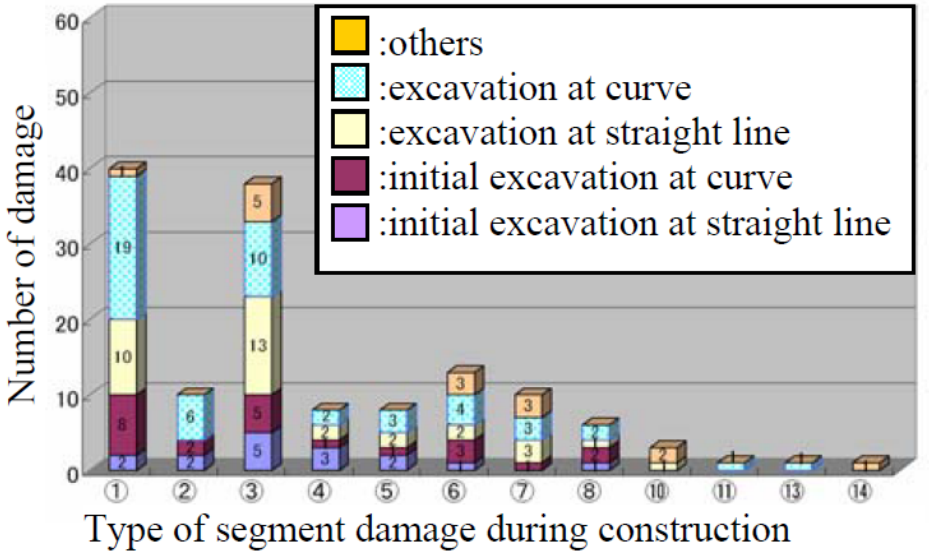
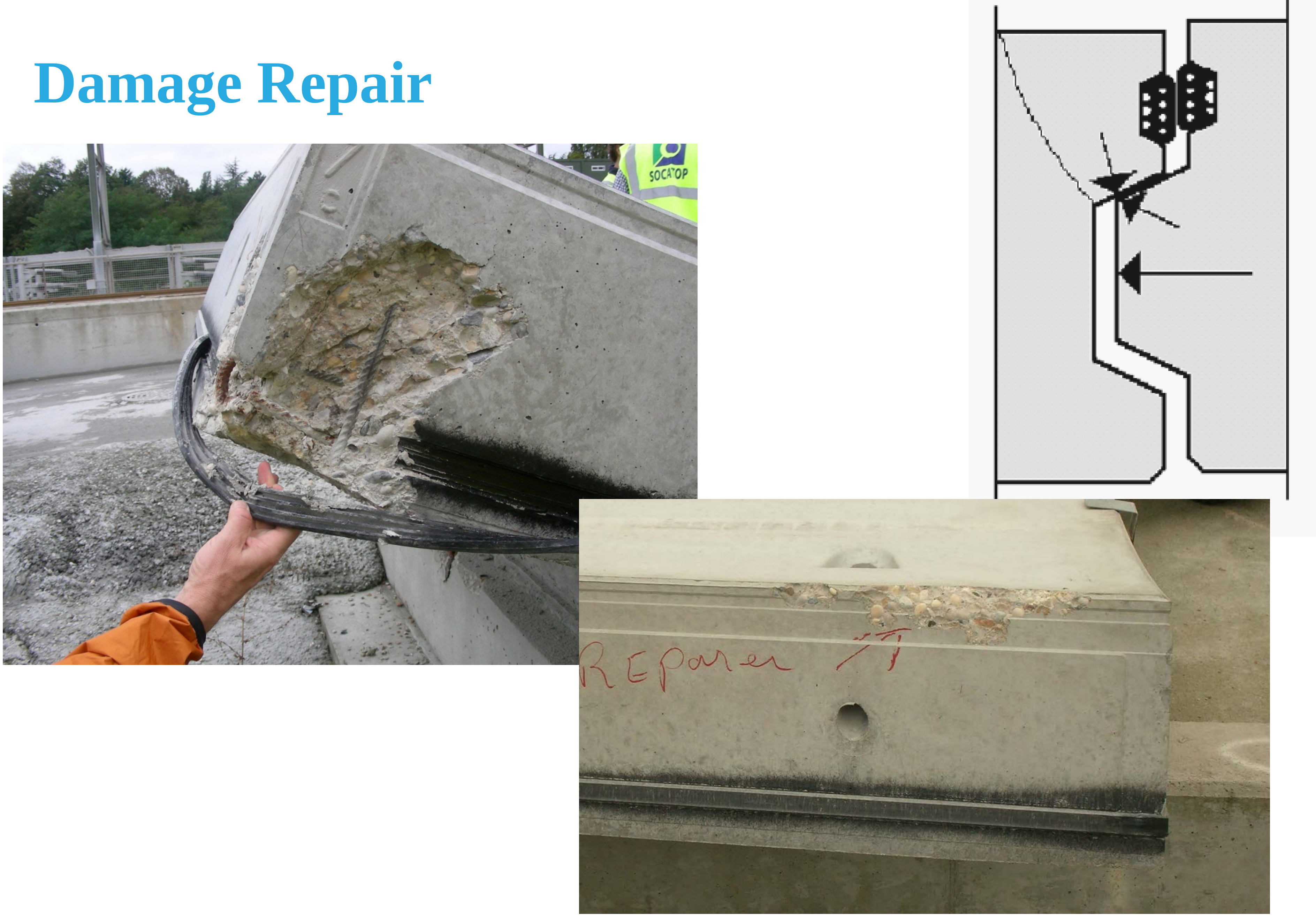
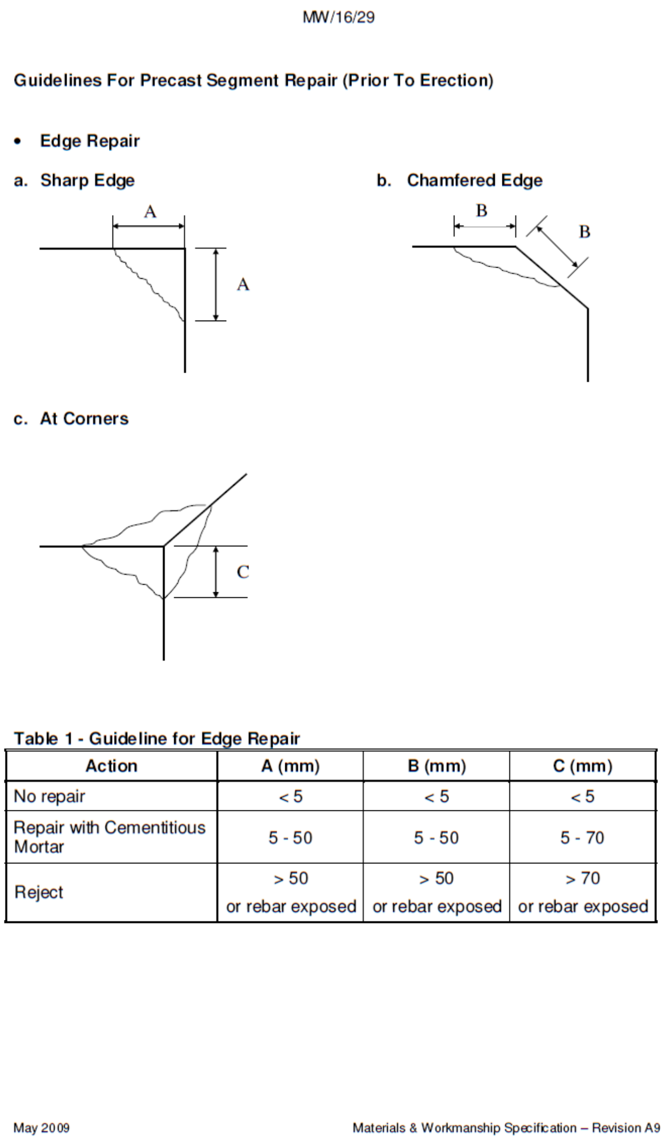


Figure 2. Construction stage at segment damage appearance (JSCE, 2005, p.19)

Damage Repair





MW/16/29

Guidelines For Precast Segment Repair (Prior To Erection)

- **Edge Repair**

a. Sharp Edge

b. Chamfered Edge

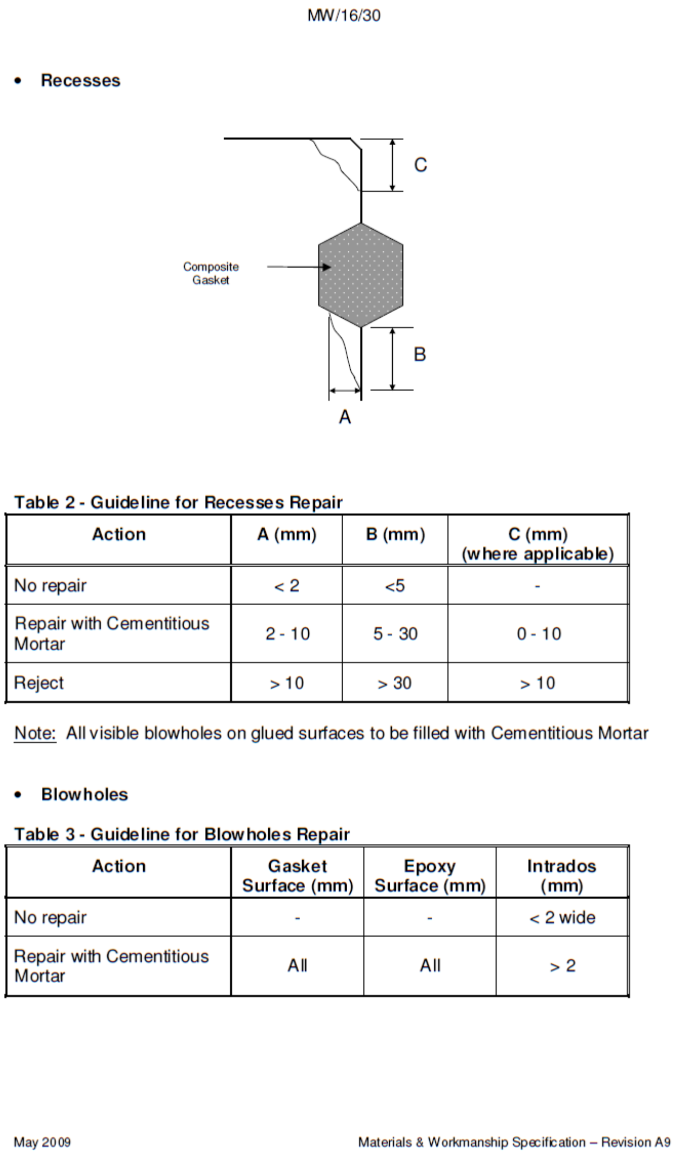
c. At Corners

Table 1 - Guideline for Edge Repair

Action	A (mm)	B (mm)	C (mm)
No repair	< 5	< 5	< 5
Repair with Cementitious Mortar	5 - 50	5 - 50	5 - 70
Reject	> 50 or rebar exposed	> 50 or rebar exposed	> 70 or rebar exposed

May 2009

Materials & Workmanship Specification – Revision A9


C
Composite Gasket
B
A

MW/16/30

- **Recesses**

Table 2 - Guideline for Recesses Repair

Action	A (mm)	B (mm)	C (mm) (where applicable)
No repair	< 2	<5	-
Repair with Cementitious Mortar	2 - 10	5 - 30	0 - 10
Reject	> 10	> 30	> 10

Note: All visible blowholes on glued surfaces to be filled with Cementitious Mortar

- **Blowholes**

Table 3 - Guideline for Blowholes Repair

Action	Gasket Surface (mm)	Epoxy Surface (mm)	Intrados (mm)
No repair	-	-	< 2 wide
Repair with Cementitious Mortar	All	All	> 2

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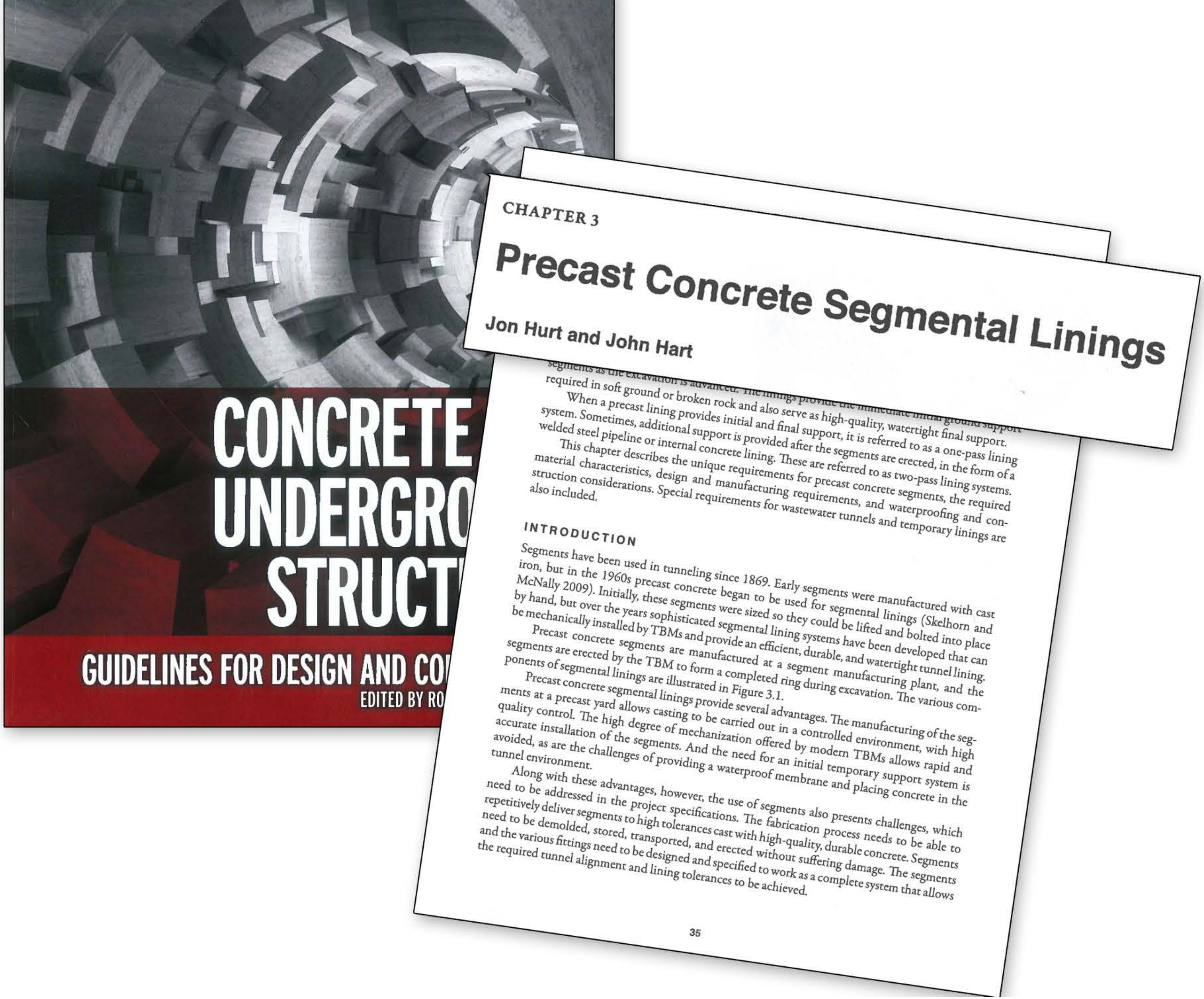

CHAPTER 3

Precast Concrete Segmental Linings

Jon Hurt and John Hart

segments as the excavation is advanced. The linings provide the immediate initial ground support required in soft ground or broken rock and also serve as high-quality, watertight final support.

When a precast lining provides initial and final support, it is referred to as a one-pass lining system. Sometimes, additional support is provided after the segments are erected, in the form of a welded steel pipeline or internal concrete lining. These are referred to as two-pass lining systems.

This chapter describes the unique requirements for precast concrete segments, the required material characteristics, design and manufacturing requirements, and waterproofing and construction considerations. Special requirements for wastewater tunnels and temporary linings are also included.

INTRODUCTION

Segments have been used in tunneling since 1869. Early segments were manufactured with cast iron, but in the 1960s precast concrete began to be used for segmental linings (Skelhorn and McNally 2009). Initially, these segments were sized so they could be lifted and bolted into place by hand, but over the years sophisticated segmental lining systems have been developed that can be mechanically installed by TBMs and provide an efficient, durable, and watertight tunnel lining.

Precast concrete segments are manufactured at a segment manufacturing plant, and the segments are erected by the TBM to form a completed ring during excavation. The various components of segmental linings are illustrated in Figure 3.1.

Precast concrete segmental linings provide several advantages. The manufacturing of the segments at a precast yard allows casting to be carried out in a controlled environment, with high quality control. The high degree of mechanization offered by modern TBMs allows rapid and accurate installation of the segments. And the need for an initial temporary support system is avoided, as are the challenges of providing a waterproof membrane and placing concrete in the tunnel environment.

Along with these advantages, however, the use of segments also presents challenges, which need to be addressed in the project specifications. The fabrication process needs to be able to repetitively deliver segments to high tolerances cast with high-quality, durable concrete. Segments need to be demolded, stored, transported, and erected without suffering damage. The segments and the various fittings need to be designed and specified to work as a complete system that allows the required tunnel alignment and lining tolerances to be achieved.

35